

DEEP-SEA RESEARCH

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DEEP-SEA RESEARCH

Editors

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I. GENERAL

1. Papers should be submitted to the editor for the appropriate country. Papers submitted for publication will naturally be judged from the standpoint of scientific originality and novelty. Technical details of apparatus used in scientific investigation can, however, be presented in brief notes. The preparation of progress reports and review articles is invited by the editors from time to time, and it is therefore requested that no uninvited contributions of this nature be submitted. The journal appears quarterly, four issues making up one volume.

2. Only papers that have not been previously published can be accepted for publication in *Deep-Sea Research*.

3. 50 free reprints of each paper will be provided. Additional copies can be purchased if ordered at the time the first proofs are returned. A reprint order form will be sent with the galley proofs.

II. SCRIPT REQUIREMENTS

1. Scripts should be typed. The text must be ready for printing and should be carefully checked for errors. Authors will receive proofs for correction.

2. Half-tone illustrations are to be restricted to the minimum necessary. They should accompany the manuscript, mounted on separate sheets. Line drawings should include all relevant details and it is particularly requested that originals and not photo-prints should be sent. Photographs should be enlarged sufficiently to permit their clear reproduction in half-tone. If words or numbers appear in photographs, two copies are requested, one clearly printed and the other without inscription. Illustrations should be made to fit within the type area after reduction, where at all possible.

3. References to published literature should be quoted in the text as follows: SMITH (1950) - the date of publication, in parentheses, following the author's name. References should be listed together at the end of each paper and not given as footnotes. They should be arranged in alphabetical order (first author's surname) to appear as follows :

BULLARD E. C. (1954) Heat-flow through the floor of the ocean.
Deep-Sea Res. **1**, 65-66.

PETTERSSON H. and ROTSCHI H. (1952) The nickel content of deep-sea deposits. *Geochim. et. Cosmochim. Acta* **2**, 81-90.

It is particularly requested that (a) author's initials, (b) title of the paper, and (c) the volume or part numbers and page numbers be given in every case.

4. The text of articles submitted should be concise and in a readily understandable style. The essential contents of each paper should be briefly recapitulated in an abstract, which will appear at the head of the paper.

5. To conserve space authors are requested to mark less important portions of their papers for printing in smaller type.

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Analysis of sound-scattering observations from non-uniform distributions of scatterers in the ocean

STEFAN MACHLUP and J. B. HERSEY

Abstract—A method is described for computing the vertical distribution of volume-scattering coefficient from a scattering experiment in which an explosion is used as the sound source, and a hydrophone having specified directional properties feeds a recorder through a band-pass filter.

Formulae for the echoes from several model distributions of scatterers are derived as functions of time and frequency. The information about marine scatterers obtainable from the scattering spectrum is discussed.

I. INTRODUCTION

SOUND scattering by both nekton and plankton has been one of the very intriguing problems in marine science for the past decade. Sound has proved to be an effective tool for revealing the presence and something of the behaviour of marine life, some of which could be identified, but most of which could not. Commercial fisheries have been able to do most of the identifying because they have followed up their acoustical observations with large-scale fishing operations, usually in rather shallow water. By contrast, no positive identification has been made of sound-scattering life in the deep scattering layers, partly because of inadequate fishing gear for the problem, and partly because the layers are found only in deep water and probably seldom represent dense concentrations. Most, if not all of the identifications have been made from a comparison of fish caught by net hauls or explosives with the characteristics of the echo sounder record. This sort of identification may eventually be useful in studying the deep water scattering layers, but not until we have made the first positive identifications and, in addition, learned how to interpret the characteristics of the acoustic records. As a step in this learning process we and others at Woods Hole have been studying the scattering layers in the deep ocean, using a small explosive charge as the sound source instead of the usual echo sounder. The explosion is an intense source of sound over a wide range of frequencies, and was anticipated to provide a means of discovering the frequency variation of scattering from the scattering layers in some detail. HERSEY, JOHNSON and DAVIS (1952) showed that there are scattering layers at different depths and different frequencies, and HERSEY and BACKUS (1954) have found evidence for a direct dependence of the peak frequency of certain scattering layers on their depth, suggesting that many of the sound scatterers in the layers are fish with swim bladders. Other work is in progress to use this general approach to the identification problem. The present paper discusses the kind of information to be found in the usual type of recording obtained by firing a shot at shallow depth, and receiving the scattered sound with a directional transducer pointing vertically downward near the shot. The first part is equally applicable to the analysis of volume scattering in general, and the rest considers the various questions having to do with analyzing the complex scattered sound from the shot with band-pass filters.

Typical observations at sea are made by detonating an explosive charge ($\frac{1}{2}$ lb. TNT) at a shallow enough depth to blow out, thus eliminating the multiple sound pulses caused by oscillations of the gas globe. The scattered sound as well as the direct shock wave from the shot is received by a nearby hydrophone, either a circular piston type transducer pointed vertically downward or an omnidirectional hydrophone a few feet below the surface. In the early work the transducer fed a five channel amplifier, each channel of which was filtered by a rather narrow band-pass filter, so chosen as to cover a wide frequency range (cir. 1 to 20 kc). The channel outputs were rectified and recorded by an oscillograph camera. These recordings are described in more detail in HERSEY, JOHNSON and DAVIS (1952), and a sample record is shown in Fig. 1. Since 1951 single or dual channel amplifiers having a flat response over a wide frequency range have been used (cir. 100 to 15,000 or 30,000 cps.) to feed magnetic tape recorders of appropriate frequency range. These records are then played back through suitable filter systems for analysis. In the discussion below a sample analysis is presented from the earlier oscillograph records.

II. THE ANALYSIS

The problem discussed below may briefly be stated : Given an echo, what is the distribution of targets that caused it ? It is evident that we shall have to be satisfied with fragmentary information about the distribution ; there is the fundamental limitation of having only one signal (one receiver, hence one scalar function of one variable, time) to investigate a three-dimensional distribution. There is also the technical limitation on time resolution imposed by the finite length of any useful signal, and the finite response time of receiving and recording gear. The first limitation implies that one must make simplifying assumptions about the distribution to remove the indeterminacy. The second implies that the optimal description of the distribution will be in terms of averages over volumes whose dimensions have lower limits set by the time resolution.

We are interested in the frequency dependence of the scattering ; hence we must know how to separate out other frequency-dependent factors. The frequency spectrum of the outgoing energy – the explosion – can be arrived at theoretically (Section VI). So can the response of a filter to an impulsive signal (Section VII). The frequency dependence of the apparatus is taken care of by calibration at various frequencies. But one factor influences the " geometry " of the situation ; the resolution in *angle* is governed by the (frequency-dependent) directivity pattern of the receiver.

We shall discuss the echoes obtained from characteristic types of distributions, first for a non-directional receiver (low frequencies or small transducer) and then, briefly, for a directional receiver (higher frequencies or large transducer). Then we shall treat the general method of translating echo intensity (function of time) into volume scattering coefficient (function of depth).

Equation for the Echo.

If the energy flow per unit solid angle from the source of sound (assumed isotropic) is given by $F(\tau)$ (where τ is time measured from " the beginning of the signal "), then the intensity in a region of scatterers distant r from the source is $F(\tau)/r^2$. (For the moment, the acoustic approximation is assumed to hold, and dissipation is neglected). Let the differential cross-section for backward scattering of a unit volume

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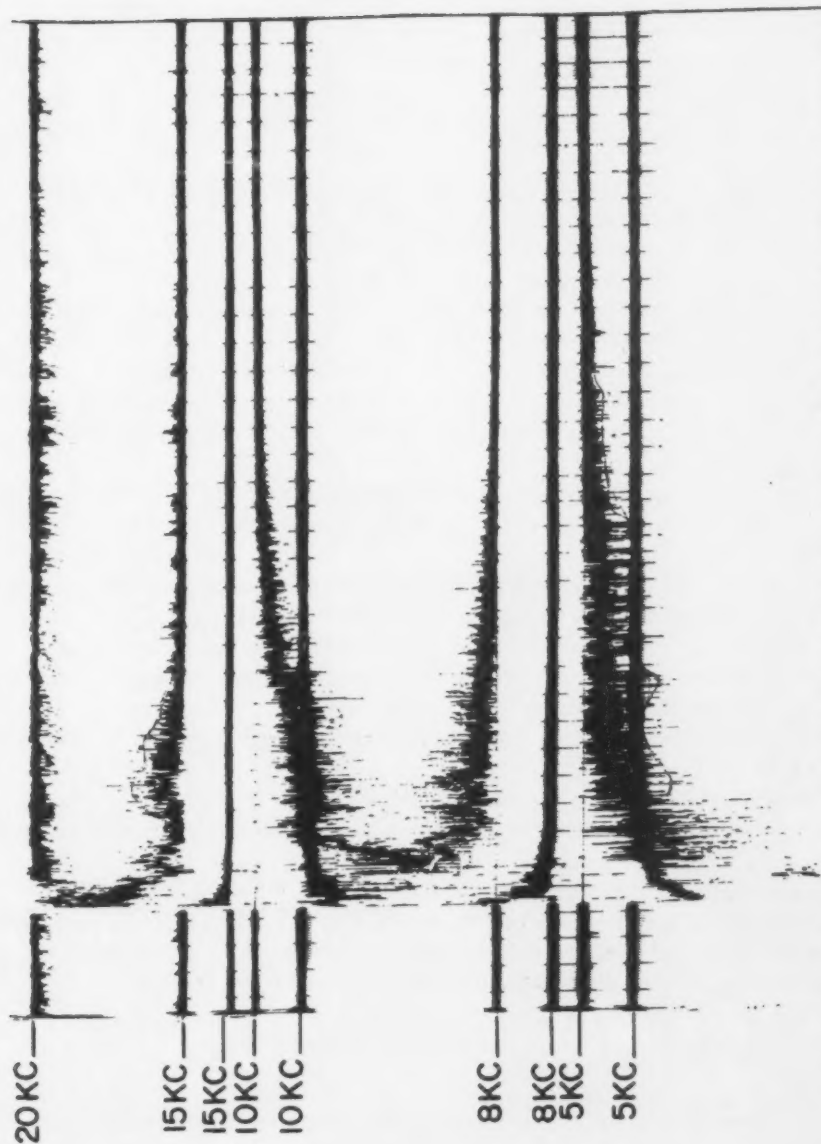


Fig. 1. 5 Channel amplifier record # 141, *Atlantis* cruise 160 made at 1113Q, 3rd April, 1950, Lat. $28^{\circ} 03'N$, Long. $54^{\circ} 10'W$.

of ocean be m . (This "backward-scattering coefficient" is smaller than the usual "total scattering coefficient" (UCDWR, 1946) by a factor $1/(4\pi)$). Then the intensity of scattered sound at the receiver (considered coincident with the source) at time t is

$$\begin{aligned} 2-1 \quad I(t) &= \int_{\text{VOLUME}} \frac{F(\tau)}{r^2} \frac{m(r, \theta, \psi) b(\theta, \psi) dV}{r^2} \\ &= \int_{\tau=0}^t \int_{\theta=0}^{\pi/2} \int_{\psi=0}^{2\pi} \frac{F(\tau)}{r^2} \frac{m(r, \theta, \psi) b(\theta, \psi)}{r^2} r^2 \sin \theta dr d\theta d\psi \end{aligned}$$

where

$$2-2 \quad r = \frac{c}{2} (t - \tau).$$

c is the velocity of sound in the ocean, taken as constant. $(t - \tau)$ is the travel time out and back. $b(\theta, \psi)$, the "directivity function" of the receiver, is the ratio of the sensitivity of the receiver to plane waves coming from the direction (θ, ψ) to its sensitivity to plane waves coming in parallel to its axis.

The assumptions on which eq. (1) is based are those made in the standard treatments of volume reverberation (UCDWR, 1946):

(1) Reverberation intensity from a given volume element is proportional to its volume. The proportionality constant is our coefficient m . The effect of this assumption is to "smear out" the individual scatterers into a continuum; this is the averaging process mentioned above.

(2) A volume element begins to scatter sound at the instant it is insonified, and stops as soon as it is again "in the dark"; i.e., there are no time lags - no storage of energy in the scatterers.

(3) Scattering cross-sections are small enough for us to neglect multiple scattering as well as attenuation of the outgoing beam due to scattering.

(4) The average reverberation intensity at the receiver is equal to the sum of the average intensities due to individual scatterers. This is a "randomizing" assumption, to average out interference effects.

(5) The backward-scattering coefficient m is independent of the direction of incidence of the beam.

To these we shall add two more assumptions:

(6) The receiver has axial symmetry [$b(\theta, \psi) = b(\theta)$] and is pointed vertically down.

(7) The scattering coefficient m is a function only of depth $z = r \cos \theta$. Any horizontal plane is a surface of equal density of scatterers. It is this most unrealistic assumption which removes the indeterminacy in solving eq. (2-1) for m given $I(t)$.

Now we can perform the ψ -integration in (2-1), which becomes

$$\begin{aligned} 2-3 \quad I(t) &= 2\pi \int_{\tau=0}^t \int_{\theta=0}^{\pi/2} \frac{F(\tau)}{r^2} m(r \cos \theta) b(\theta) \sin \theta d\theta dr \\ &= \frac{4\pi}{c} \int_{\tau=0}^t \int_{\theta=0}^{\pi/2} \frac{F(\tau)}{(t-\tau)^2} m\left[\frac{c}{2}(t-\tau) \cos \theta\right] b(\theta) \sin \theta d\theta d\tau \end{aligned}$$

using 2-2 to eliminate r .

For short signals, $F(\tau)$ is considerable only for $\tau \ll t$, and the τ -integration can

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be performed by setting $r = \frac{c}{2} t$. The total energy leaving the source is

$$2.4 \quad E = 4\pi \int_0^\infty F(\tau) d\tau;$$

thus we can simply rewrite the echo intensity as

$$2.5 \quad I(t) = \frac{Ec}{4r^2} \int_0^{\pi/2} m(r \cos \theta) b(\theta) \sin \theta d\theta.$$

This approximation limits the time resolution to times longer than the effective "signal length."

III. ECHOES WITH NON-DIRECTIONAL RECEIVER

We consider a receiver whose sensitivity is essentially the same at all angles of incidence less than $\pi/2$,

$$b(\theta) = 1,$$

and look at the time-dependence of the echo from some simple distributions of scatterers.

(i) Uniform Distribution of Scatterers.

For the case $m = \text{constant}$, the echo simply falls off as t^{-2} . (In theory it is infinite at $t = 0$).

(ii) Very Thin Layer at Depth D .

Converting to an integral over depth $z = r \cos \theta$, we have

$$I(t) = \frac{Ec}{4r^2} \int_0^r m(z) \frac{dz}{r} = \begin{cases} 0 & \text{for } t < 2D/c \\ \frac{Ec}{4r^3} \int_D^{D+r} m(z) dz & \text{for } t > 2D/c. \end{cases}$$

Qualitatively: The wave-front "dips into" the layer, is "through it" in a very short time (rise-time of the echo), whereafter the echo falls off as t^{-3} .

(iii) Uniform m Below Depth D .

$$m(z) = \begin{cases} 0 & \text{for } z < D \\ m & \text{for } z > D \end{cases}$$

$$I(t) = \begin{cases} 0 & \text{for } t < 2D/c \\ \frac{Ec}{4r^2} \int_D^r m \frac{dz}{r} = \frac{Ecm}{4} \frac{r-D}{r^3} & \text{for } t > 2D/c. \end{cases}$$

As the wave-front "dips into" the layer, the echo builds up, reaching a maximum at $t = \frac{2}{c}(1.5D)$, then falling off, becoming, as $r > D$, asymptotic to t^{-2} . (See

"uniform distribution of scatterers"). The curve $I(t)$ is plotted on a dimensionless time scale in Fig. 2 (solid curve), for a layer beginning at depth $D = 1$. $Ec m/4$ has been arbitrarily taken as unity.

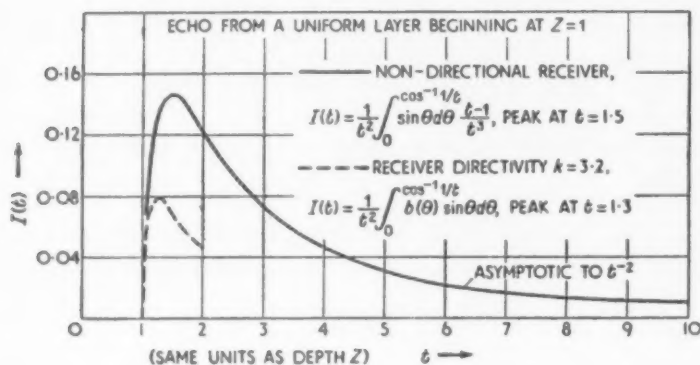


Fig. 2.

(iv) *Layer of Uniform m between Depths D_1 and D_2 .*

Here three regions must be distinguished :

$$z < D_1, \quad m(z) = 0, \quad I(t) = 0$$

$$\left[t < \frac{c}{2} D \right]$$

$$D_1 < z < D_2, \quad m(z) = m, \quad I(t) = \frac{Ec m}{4} \frac{r - D}{r^3}$$

$$\left[\frac{c}{2} D_1 < t < \frac{c}{2} D_2 \right]$$

This is as in (iii) : The echo does not yet "know" that the layer is going to end.

$$z > D_2, \quad m(z) = 0, \quad I(t) = \frac{Ec}{4r^2} \int_{D_1}^{D_2} m \frac{dz}{r}$$

$$\left[t > \frac{c}{2} D_2 \right] \quad = \frac{Ec}{4r^3} m (D_2 - D_1)$$

(Compare ii). A plot of $I(t)$ in decibels appears in Fig. 3 (solid curve), on a logarithmic time scale, for $D_1 = 1$, $D_2 = 2$; same normalization as above.

(v) *Gaussian Distribution of Scatterers.*

Such a distribution is given by

$$m(z) = m \frac{2}{\sqrt{\pi}} e^{-\frac{(z-D)^2}{2\sigma^2}}$$

for $z > 0$. The distribution centres at depth D , has e^{-1} ($= .606$) of its peak density at σ units above and below D . Then

$$I(t) = \frac{Ec}{4r^2} m \frac{2}{\sqrt{\pi}} \int_0^{\pi/2} e^{-\frac{(z-D)^2}{2\sigma^2}} \sin \theta d\theta.$$

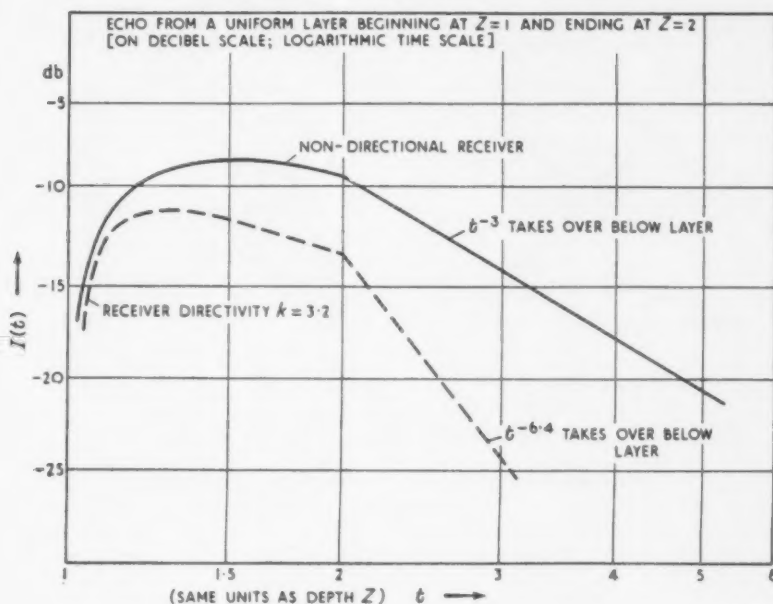


Fig. 3.

For simplicity we measure depth in units of $\sigma \sqrt{2}$ and echo intensity in units of $Ecm/4$. We must distinguish two regions :

$$r < D \quad I(t) = \frac{1}{r^3} \{ \Phi(D) - \Phi(D-r) \}$$

$$\left[t < \frac{c}{2} D \right]$$

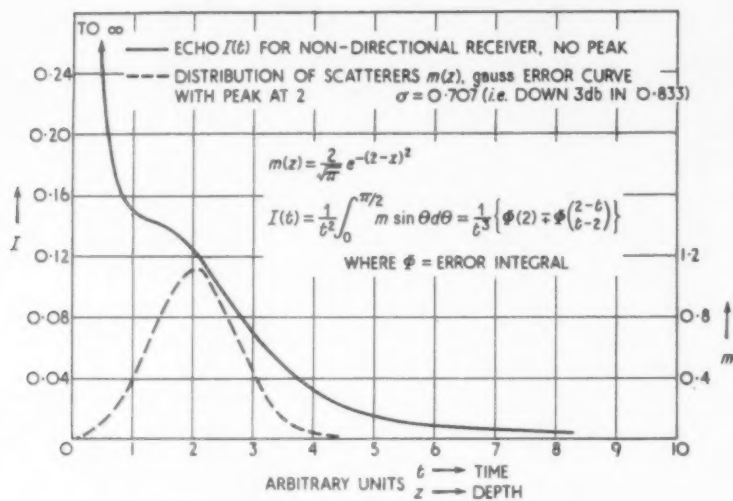
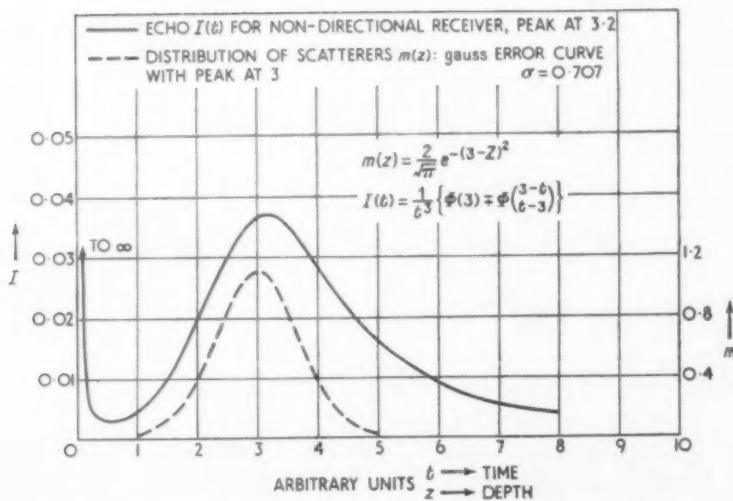
$$r > D \quad I(t) = \frac{1}{r^3} \{ \Phi(D) + \Phi(r-D) \},$$

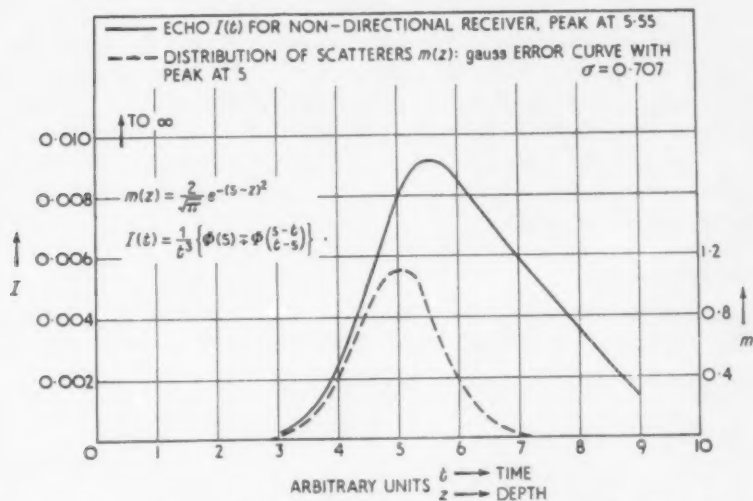
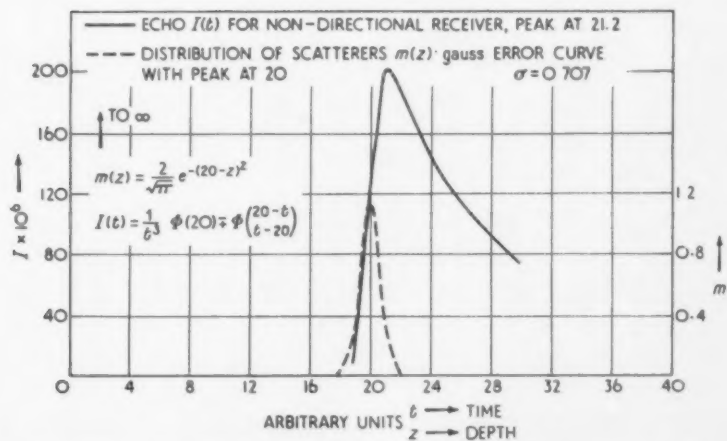
$$\left[t > \frac{c}{2} D \right]$$

where

$$\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy$$

is the "error integral," tabulated in JAHNKE and EMDE (1945). The distribution and the echo are plotted for various values of D in Figs. 4-7. Since there are scatterers at $z = 0$, the echo is theoretically infinite at $t = 0$. For a deep enough (or thin enough) layer (Figs. 5-7), it falls to a minimum, peaks as the wave-front "dips" well into the dense part of the layer, and then falls off asymptotic to t^{-3} . Its peak is somewhat later than it would be with a very directional receiver. For a shallow

Fig. 4. Echo from a Gaussian distribution of scatterers centered at $z = 2$.Fig. 5. Echo from a Gaussian distribution of scatterers centered at $z = 3$.

Fig. 6. Echo from a Gaussian distribution of scatterers centered at $z = 5$.Fig. 7. Echo from a Gaussian distribution of scatterers centered at $z = 20$.

(or thick) layer (Fig. 4), it never goes to a minimum, and has a "ripple" instead of a peak.

IV. ECHOES WITH A DIRECTIONAL RECEIVER

When the receiver sensitivity is isotropic (non-directional), the time dependence and frequency dependence of the echo are separable. This is not true, however, for a directional receiver, since the directivity function depends on frequency and appears in the integrand of the expression giving the time dependence. Thus, whether we consider the echo as a function of time in a given frequency band, or as a function of frequency at a given instant of time, our curve will depend on the whole distribution of scatterers.

Directivity Function.

If the receiver is treated as a freely vibrating circular piston in an infinite, rigid baffle, theory predicts a directivity function (MORSE, 1948)

$$b(\theta) = \left| \frac{2J_1(k \sin \theta)}{k \sin \theta} \right|^2 \quad (4-1)$$

where

J_1 = Bessel function of order one

$k = \pi d/\lambda$ = dimensionless number proportional to frequency and receiver size

d = diameter of the piston

$\lambda = c/f$ = wave-length, in the transmitting medium, of sound of frequency f .

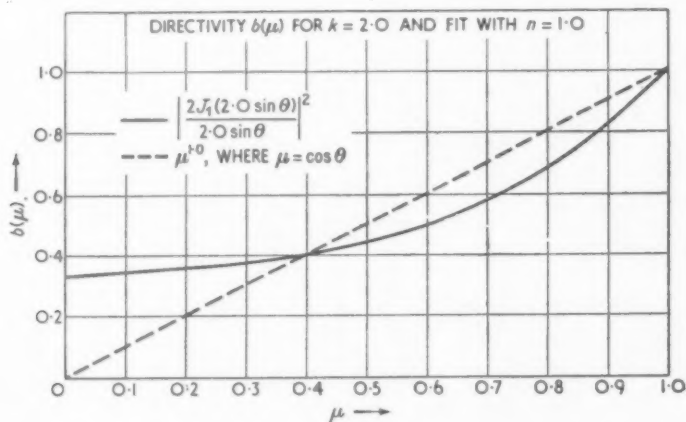


Fig. 8.

This function is tabulated in Table I as far as its first zero, i.e., out to the end of the "main lobe." The argument $\phi = k \sin \theta$ permits rapid use of the table for any frequency and receiver diameter. $b(\theta)$ is plotted against the argument $\mu = \cos \theta$ in Figs. 8-10 (solid curves) for $k = 2.0$, $k = 3.2$, and $k = 5.3$. (Side lobes on $k = 5.3$ not shown.)

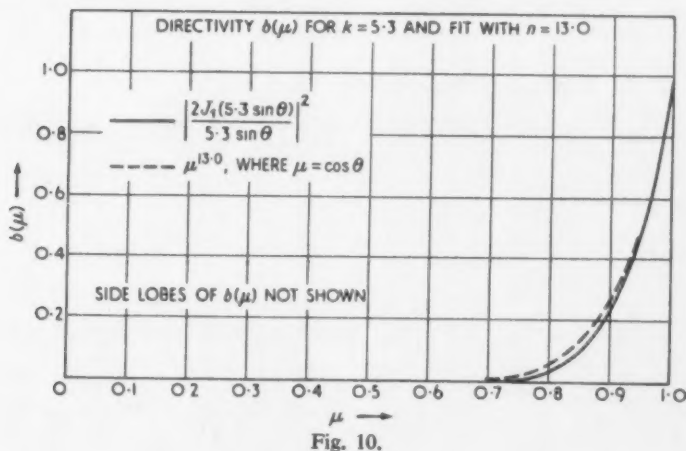
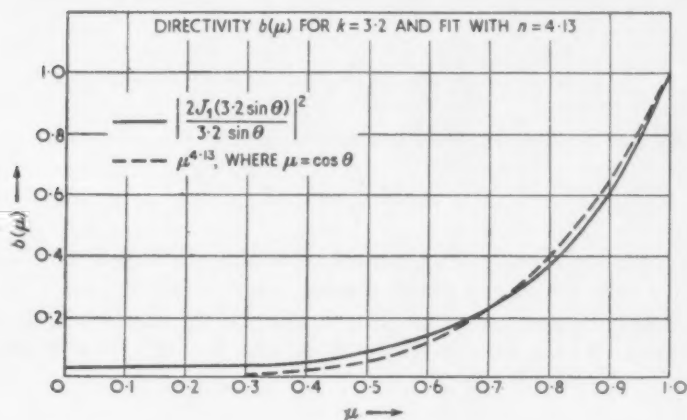
The conventional directivity index,

$$N_{DI} = -10 \log \frac{1}{2} \int_0^\pi b(\theta) \sin \theta d\theta$$

becomes, for this theoretical directivity function,

$$4-2 \quad N_{DI} = -10 \log \frac{1}{2} \int_0^\pi \left| \frac{2J_1(k \sin \theta)}{k \sin \theta} \right|^2 \sin \theta d\theta \cong +20 \log k \quad \text{for } k > 1$$

(MORSE, 1948).



Directivity Calibration.

The hydrophone is calibrated off the ship in an experimental set-up. The results of this calibration are used in the final calculation of scattering coefficient. The frequency dependence of the directivity does not agree well with theory, but by choosing an "effective diameter" for each frequency, a good fit to the theoretical curves can be obtained at frequencies where the side lobes are not important. By

integrating for N_{DI} numerically (see section VIII), k effective is chosen to satisfy $N_{DI} = +20 \log k$.

Approximate Directivity Function.

In section (V) it will be seen that it is desirable to find a simpler analytic function for $b(\theta)$ than the one given above, even if this new function has no theoretical significance. The function $\cos^n \theta$ has been tried. The condition on n shall be that the total energy received shall be the same for the "fit" function as for the theoretical one; hence that

$$\int_0^\pi \left| \frac{2J_1(k \sin \theta)}{k \sin \theta} \right|^2 \sin \theta d\theta = \int_0^{\pi/2} \cos^n \theta \sin \theta d\theta.$$

Using eq. 4-2 and performing the integrations, one obtains

$$4.3 \quad n = \frac{k^2}{2} - 1.$$

The dotted curves on Figs. 8-10 show the fit obtained. At high frequencies (large k) the fit is good close to the axis (small angles), where it matters most. It does not, of course, follow the side-lobes, nor does it ever cut off completely, as the Bessel function J_1 does. At low frequencies the fit is poor, but here the approximation of non-directionality becomes good.

Echoes from simple distributions.

Using the approximate directivity function $b(\mu) = \mu^n$ we now look at the echoes from some of the model distributions: (No confusion should be caused by use of the function symbol $b(z/r)$ when the argument is $\mu = \cos \theta$ instead of θ).

(i) Thin Layer at Depth D . (Sec. III, case ii).

The echo begins at $t = 2D/c$. It rises quickly, and then falls off according to

$$\begin{aligned} I(t) &= \frac{Ec}{4} \frac{1}{r^2} \int_0^r m(z) b\left(\frac{z}{r}\right) \frac{dz}{r} \\ &= \frac{Ec}{4} \frac{1}{r^3} b(D/r) \int_D^{D+d} m(z) dz \\ &= \frac{Ec}{4} \frac{1}{r^{3+n}} D^n \int_D^{D+d} m(z) dz \quad [\text{this form displays the time dependence: } t = 2r/c]. \\ &= \frac{Ec}{4} \frac{1}{r^3} (D/r)^{\frac{k^2}{2}-1} \int_D^{D+d} m(z) dz \quad [\text{this form displays the frequency dependence: } f = kc/\pi d]. \end{aligned}$$

This frequency dependence is shown graphically in Fig. 11 for time instants just after the beginning of the echo.

For very high frequencies (strongly directional receiver: narrow directivity pattern) the fall-off with time is so fast that the echo is just a sharp "spike." Then, in the integrand, $z \cong r$, ($\cos \theta \cong 1$) where $b(\theta)$ is appreciable, and we have

$$I(t) = \frac{Ec}{4r^2} m(r) \int_0^1 b(\mu) d\mu.$$

This is a case in which the frequency dependence can be separated out, since the integral no longer contains the time, and is, in fact, equal to $1/k^2$ (see eq. 4-2, and the definition of the directivity index).

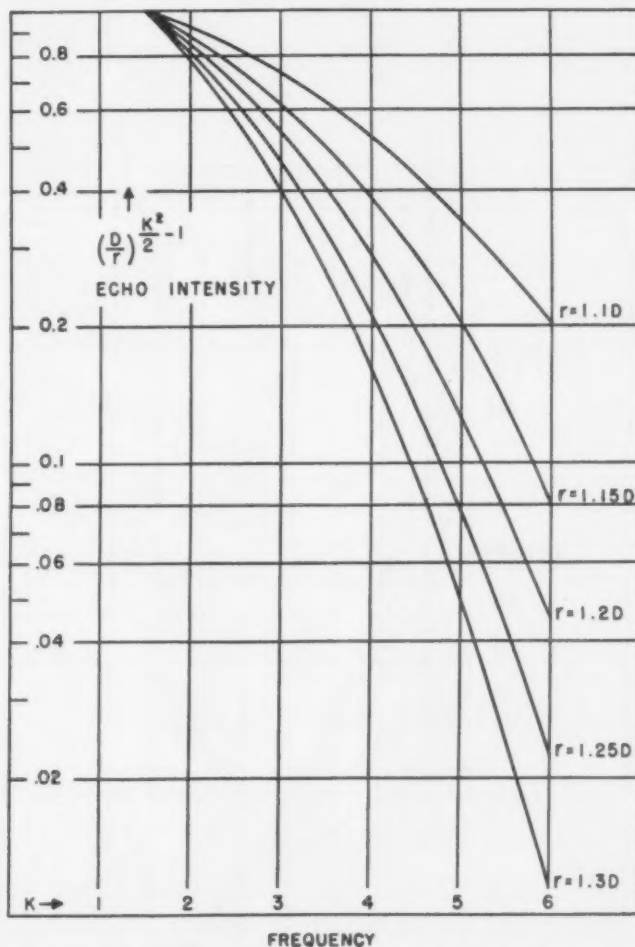


Fig. 11. Frequency dependence of the echo from a thin layer at depth D (directional receiver).

Of course, any distribution can be considered a superposition of thin layers, and we see that, for a very directional receiver, the echo is just proportional to the scattering coefficient corrected for $1/r^2$ "spreading loss". More simply stated: $t^2 I(t)$ gives a true picture of the depth distribution of scatterers.

(ii) *Uniform m Below Depth D . (Sec. III, case iii).*

Again, the echo begins at $t = 2D/c$. Thereafter

$$I(t) = \frac{Ec}{4} \frac{m}{r^2} \int_D^r b(z/r) \frac{dz}{r}$$

$$\begin{aligned}
 &= \frac{Ec}{4} \frac{m}{r^2} \int_D^r \left(\frac{z}{r}\right)^n \frac{dz}{r} \\
 &= \frac{Ec}{4} \frac{m}{r^2} \frac{1}{n+1} [1 - (D/r)^{n+1}] \\
 &= \frac{Ec}{4} \frac{m}{r^2} \frac{2}{k^2} [1 - (D/r)^{k^2/2}].
 \end{aligned}$$

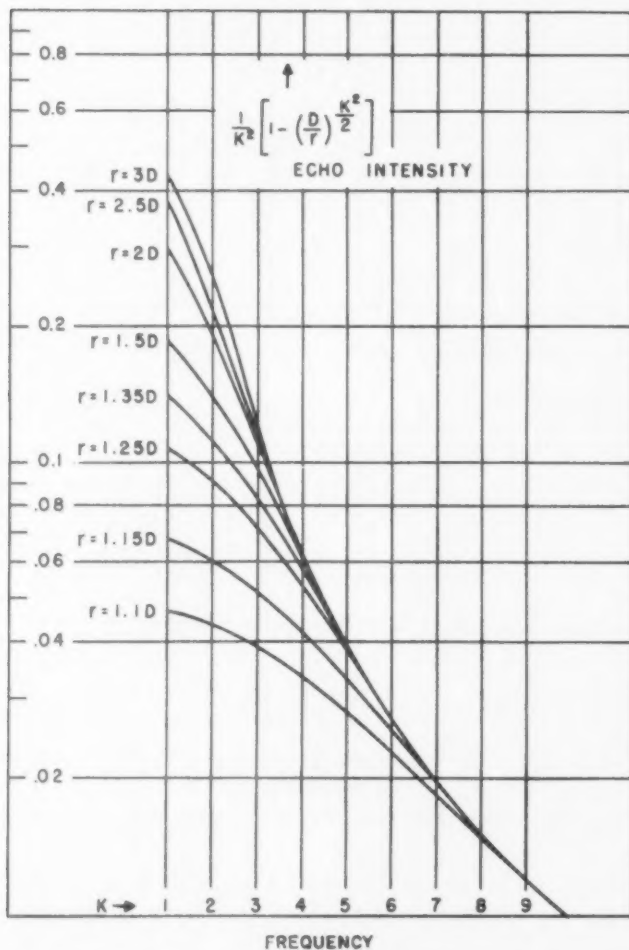


Fig. 12. Frequency dependence of the echo from a uniform distribution of scatterers below depth D (directional receiver).

The time dependence is shown in Fig. 2 for $k = 3.2$. The frequency dependence is shown in Fig. 12 for time instants just after the beginning of the echo.

(iii) *Layer of Uniform m Between Depths D_1 and D_2 . (Sec. III, case iv).*

For $t < 2D_2/c$ this is identical with (ii). Thereafter (the wave front being "through" the layer)

$$\begin{aligned} I(t) &= \frac{Ec}{4} \frac{m}{r^2} \int_{D_1}^{D_2} b\left(\frac{z}{r}\right) \frac{dz}{r} \\ &= \frac{Ec}{4} \frac{m}{r^2} \int_{D_1}^{D_2} \left(\frac{z}{r}\right)^n \frac{dz}{r} \\ &= \frac{Ec}{4} \frac{m}{r^{3+n}} \frac{1}{n+1} [D_2^{n+1} - D_1^{n+1}] \quad (\text{this form displays the time dependence}) \\ &= \frac{Ec}{4} \frac{m}{r^2} \frac{2}{k^2} \left[\left(\frac{D_2}{r}\right)^{k^{1/2}} - \left(\frac{D_1}{r}\right)^{k^{1/2}} \right] \quad (\text{this form displays the frequency dependence}). \end{aligned}$$

The time dependence is shown in Fig. 2 for $k = 3.2$. It may be instructive to note how this formula goes over into that of case (i) for a thin layer.

V. SOLUTION OF THE INTEGRAL EQUATION

Thus far $m(z)$ was considered given and $I(t)$ calculated. In practice, $I(t)$ appears on the records and $m(z)$ is to be found: The solution of an integral equation is required (Fredholm equation of the first kind):

$$I(t) = \frac{Ec}{4} \frac{1}{r^2} \int_0^1 m(r\mu) b(\mu) d\mu.$$

This is equation (2-5) with $\mu = \cos \theta$ (Recall that $r = ct/2$).

The solution can be obtained in closed form when $b(\mu)$ is of the form μ^n , and this was our motivation for choosing this form for the "approximate directivity function" in the preceding section. Writing $\mathcal{J}(r) = I(t)$, we have

$$5-1 \quad m(z) = \frac{1}{z^n} \frac{d}{dz} \left[\frac{4}{Ec} z^{n+3} \mathcal{J}(z) \right].$$

In logarithmic form, (using the relation $\frac{dy}{dx} = \frac{y}{x} \frac{d \log y}{d \log x}$) this is written

$$\begin{aligned} 5-2 \quad 10 \log m(z) &= -10 \log \frac{Ec}{4} + 20 \log z + 10 \log \mathcal{J}(z) \\ &\quad + 10 \log \frac{d \log [z^{n+3} \mathcal{J}(z)]}{d \log z}. \end{aligned}$$

In words: The shape of the depth distribution of scatterers is given by the curve $z^2 I(t)$ multiplied by the slope of the curve $z^{n+3} I(t)$ plotted on a logarithmic scale.

The term $z^2 I(t)$ is not unexpected in view of the remarks under (i) of the preceding section. The term in the slope of $z^{n+3} I(t)$ contains the effect of receiver directivity. It is also the "strong term" at the top and bottom of the layer: When the wave-front is just dipping into the layer - the echo is still small, but building up rapidly - the slope is large, showing there are many scatterers. When the wave-front is "through" the layer - the echo falls off as $t^{-(n+3)}$ - the slope is zero, showing there are no scatterers

left. Incidentally, we may note that for a non-directional receiver, $n = 0$, the echo falls off as r^{-3} below the layers, as discussed in Section III.

VI. THE ENERGY OF THE SHOCK WAVE

The total energy of the outgoing signal can be calculated from empirical formulas given by ARONS (1954). The pressure pulse is considered to be of the form $P e^{-\tau/\theta}$ ($\tau > 0$), an exponential pulse with peak pressure P and decay time θ (rise time essentially zero). For TNT,

$$6-1 \quad P = 2.16 (10^4) \left(\frac{W^{\frac{1}{3}}}{R} \right)^{1.13} \quad \text{p.s.i.}$$

$$6-2 \quad \theta = 58 (10^{-6}) W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{R} \right)^{-0.22} \quad \text{sec.,}$$

where W = weight of TNT in pounds, R = range in feet.

The empirical formulas 6-1 and 6-2 are based on considerable data from measurements on larger charges at shorter ranges than we have used in the scattering layer studies. The change of shape of the pulse with range, and the associated deviation from a $1/R$ -dependence of the peak pressure, are effects due to the finite amplitude of the shock wave, i.e., the failure of the acoustic approximation. However, for 0.5 lb. TNT charges at distances greater than about 240' (0.1 sec. echo travel time), we are well within the region where the acoustic approximation may be taken to hold. Any error resulting from our use of the formulae in the range 240' to 3,000', within which the present scattering data lie, is small compared to the uncertainty inherent in the analysis of the scattering records. According to ARONS (private communication), the error is more reasonably assigned to slightly variable performance of the TNT charges. In ARONS (1954) the maximum variation from 6-1 reported for peak pressure of 0.5 lb. TNT charges amounts to about 3 db.

At some mean distance R , the energy flow per unit solid angle is

$$6-3 \quad F(\tau) = R^2 \frac{p^2}{\rho c}$$

where p = pressure of the pulse and ρ = density of the water. The total energy E getting out through the sphere of radius R is

$$6-4 \quad E = 4\pi \int F(\tau) d\tau = 4\pi R^2 \frac{p^2}{\rho c} \int_0^\infty e^{-2\tau/\theta} d\tau \\ = 4\pi R^2 \frac{p^2 \theta}{\rho c 2}.$$

VII. RESPONSE OF THE FILTERS

The receiving gear is calibrated using sinusoidal signals, at the centre frequency of the separate filters. An investigation of the response of the filters to an exponential signal is therefore required.

The quantity of interest for each filter is the fraction A of the input energy that it puts out :

$$A = \frac{\text{Energy out}}{\text{Energy in}}$$

If the filter were perfectly flat and non-dissipative over its pass-band, and had vertical cut-off to zero at the edges, then the energy out would be the energy of the Fourier components of the input signal contained in the pass-band.

For a filter admittance approximating the actual filters, take a transfer characteristic

$$Y(\omega) = \frac{b}{b + i(\omega - \omega_0)}$$

This is normalized to unity at the centre of the band ω_0 and is down 3 db at $\omega_0 \pm b$; $2b$ may be called the "band-width."

Consider an input $p(t)$ ($t > 0$), expressed as an integral over angular frequency :

$$7-1 \quad p(t) = \int_{-\infty}^{+\infty} \psi(\omega) e^{i\omega t} d\omega,$$

i.e., $\psi(\omega)$ is the Fourier transform of $p(t)$.

The output from a network with characteristic $Y(\omega)$ is then

$$7-2 \quad v(t) = \int_{-\infty}^{+\infty} \psi(\omega) Y(\omega) e^{i\omega t} d\omega.$$

A purely dissipative (resistive) load will see the real part of $v(t)$. For an exponential input signal

$$7-3 \quad p(t) = P e^{-\lambda t} \quad (\lambda = 1/\Theta)$$

we have

$$7-4 \quad \text{Re}[v(t)] = Pa \{e^{-bt} \sin(\omega_0 t - \delta) + e^{-\lambda t} \sin \delta\},$$

where

$$a = \frac{b}{\sqrt{(\lambda - b)^2 + \omega_0^2}}$$

and $\tan \delta = \frac{\lambda - b}{\omega_0}$. The energy in a signal is proportional to the time integral of the square of the signal voltage.

Thus the energy in the input signal (7-3) is proportional to $P^2/2\lambda$; the energy in the output signal (7-4) is proportional to

$$P^2 a^2 \int_0^\infty [e^{-bt} \sin(\omega_0 t - \delta) + e^{-\lambda t} \sin \delta]^2 dt.$$

Neglecting the cross-term in the squared parenthesis, the fraction of the energy "getting through" is approximately

$$7-5 \quad A = a^2 \left\{ \frac{1}{2} \frac{\lambda}{b} + \sin^2 \delta \right\}.$$

VIII. PRELIMINARY RESULTS

Some echoes have been analyzed using the method of section V. The equation 5-2,

$$\begin{aligned} 10 \log m(z) = & -10 \log \frac{Ec}{4} + 20 \log z + 10 \log \mathcal{J}(z) \\ & + 10 \log \frac{d \log [z^{n+3} \mathcal{J}(z)]}{d \log z} \end{aligned}$$

may be written, recalling $z = \frac{c}{2} t$,

$$8-1 \quad 10 \log m(z) = -10 \log E + 10 \log c + 20 \log t + 10 \log I(t) \\ + 10 \log \frac{d \log [t^{n+3} I(t)]}{d \log t}.$$

In practice, the receiving gear has been calibrated so that the linear deflection on the galvanometer record can be read in db re 1 volt open circuit output of the hydrophone. The hydrophone has been calibrated so that this can be interpreted as db re 1 dyne/cm² sound pressure at the hydrophone incident on its axis. The effective attenuation A in the filters due to the shape of the input signal (see section VII, particularly eq. 7-5) may loosely be considered as applied to E . Then EA is the energy getting out through the "mean sphere" (see section VI) and through the filter.

With the incident intensity given in units of sound pressure p , one must recall

$$8-2 \quad I(t) = \frac{p^2(t)}{\rho c}$$

and write

$$8-3 \quad 10 \log m(z) = Q_{f_0} + 20 \log t + 20 \log e(t) \\ + 10 \log [\text{slope of } t^{n+3} e^2(t)],$$

where : 8-3-i $m(z)$ = back-scattering cross-section per unit volume,

$$8-3\text{-ii} \quad Q_{f_0} = -10 \log E - 10 \log A_{f_0} - 10 \log \left| \frac{\text{gm}}{\text{cm}^3} \right| - \text{db re 1 volt} \\ \text{open circuit hydrophone response for } 1 \frac{\text{dyne}}{\text{cm}^2} \text{ sound field}$$

$$8-3\text{-iii} \quad E = \text{energy, in ergs}$$

$$8-3\text{-iv} \quad A_{f_0} = \text{fraction of the energy getting through a filter with} \\ \text{centre frequency } f_0$$

$$8-3\text{-v} \quad t = \text{time, in seconds}$$

$$8-3\text{-vi} \quad e(t) = \text{echo, in open circuit hydrophone output. Slope is} \\ \text{taken on the db scale, with a logarithmic time scale.}$$

Some Quantitative Results.

$10 \log E = 122.8$ db re 1 erg for a $\frac{1}{2}$ lb. block of TNT, at 1,500 feet. There $\Theta = 250$ μ seconds, $\lambda = 4 (10^3)$ sec⁻¹. We use the 5 kc trace from Fig. 1 for sample analysis.

The filter is fitted by the function $Y = \beta / [\beta + i(f - f_0)]$, using 5 kc as the centre frequency and a band-width, 2β , of 0.3 kc ($\beta = \frac{1}{2\pi} b, f_0 = \frac{1}{2\pi} \omega_0$) we have $10 \log A = -22.9$ db. From the hydrophone calibration $N_{DI} = -5.9$ db, and the open circuit response per dyne/cm² is -74.5 db re 1 volt. Using 8-3-ii, $Q_{5kc} = -25.4$ db.

A sample analysis is shown in Fig. 13. For 5 kc, $k = 2.0$ gives the experimental directivity index. Hence $n = \frac{k^2}{2} - 1 = 1.0$. The following curves are shown :

- the echo $I(t)$, in db re 1 millivolt (This curve is, of course, much smoother than the actual record. Fluctuations have been averaged out visually. Also the part of the record for $t < 0.4$ sec. has been omitted since the first part is distorted, and the later part is of too high amplitude to be read).
- the curve $t^2 I(t)$, in db re 1 millivolt.
- the curve $t^4 I(t)$, arbitrary level.
- its slope in decibels.
- $m(z)$ in db re m^{-1} , obtained by solving equation 8-3.

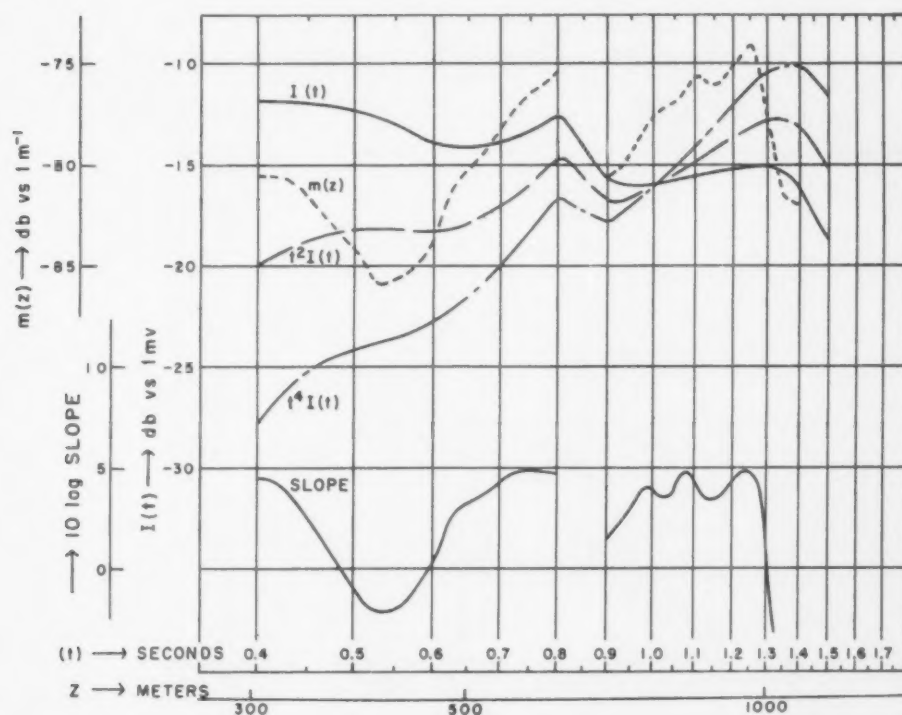


Fig. 13. Analysis of a sample record
Sargasso sea, 1113Q, 3rd April, 1950.
Echo from $\frac{1}{4}$ lb. TNT
5 kc filter, $n = 1.0$.

Note that the slope goes negative in two intervals in this example. In such instances the solution of the integral equation fails and $m(z)$ cannot be computed. The negative slope is due to the patchiness of the layers; i.e., they are not really uniform in a horizontal plane. In many recordings a reasonable smoothing of the typically spiky trace gives continuously positive slopes over most of the record.

Forty-five such traces have been thus analyzed, some for the filter centered at 5 kc as above, and some for a similar filter centred at 8 kc. There is considerable variety

both in the shape and magnitude of $m(z)$. All the records were taken in the western North Atlantic, but scarcely provide enough data to make any generalizations. The peak values of $m(z)$ range from about -60 db re M^{-1} to -77 db re M^{-1} . This compares with a range of $.5 \times 10^{-6}$ yd^{-1} to 3×10^{-7} yd^{-1} or about -63 db re M^{-1} to -65 db re M^{-1} reported by UCDWR (1946) for various higher frequencies in the Pacific. Since our sampling is completely random and small we have no way of telling whether our range is representative. Where the 5 kc and 8 kc traces from the same record could be analyzed, there are about as many instances of striking dissimilarity between them as there are of qualitative similarity. This was to have been anticipated from preliminary inspection of the data reported by HERSEY, JOHNSON and DAVIS (1952).

Table I.
Directivity Pattern: Circular Piston in an Infinite Baffle

$$b(\theta) = \left| \frac{2J_1(\phi)}{\phi} \right|^2, \quad \phi = k \sin \theta, \quad k = \pi d / \lambda$$

ϕ	$b(\theta)$	$-10 \log b(\theta)$
0.0	1.0	0.0
0.5	.935	0.3
1.0	.773	1.1
1.5	.552	2.6
1.6	.508	2.9
1.7	.462	3.3
1.8	.418	3.8
1.9	.375	4.3
2.0	.333	4.8
2.1	.292	5.3
2.2	.255	5.9
2.3	.220	6.6
2.4	.188	7.3
2.5	.158	8.0
2.6	.131	8.8
2.7	.107	9.7
2.8	.0861	10.6
2.9	.0668	11.7
3.0	.0514	12.9
3.1	.0378	14.2
3.2	.0266	15.8
3.3	.0178	17.5
3.4	.0111	19.5
3.5	.00612	22.1
3.6	.00285	25.5
3.7	.000850	30.7
3.8	.0000468	43.3
3.83		∞

IX. REMARKS CONCERNING FREQUENCY DEPENDENCE

The preceding pages have been concerned exclusively with the volume scattering coefficient, not with individual scatterers. Our aim, however, is to use our "sound spectroscopy" to find out something about the size and number of the scatterers, and ultimately to tie in with other techniques (net hauls, photography) to find out what the scatterers really are.

The acoustic scattering cross-section of a sphere as a function of frequency is discussed by ANDERSON (1950). At low frequencies, sufficiently low that the wave

length is much greater than the size of the scatterer, the cross-section varies as the fourth power of the frequency (Rayleigh scattering; only the first and second spherical harmonics contribute). This holds regardless of the shape of the scatterer. At higher frequencies, when the wave length becomes of the order of the size of the scatterer, the cross-section goes through some maxima and minima, and higher order spherical harmonics become important. Then the differential cross-section becomes a rapidly varying (oscillating) function of angle. But any finite-sized receiver sees an average over a finite range of angle. As the frequency is further increased, these averages finally become independent of frequency, and we get into the region of geometrical reflection. The exact shape of the curve depends, of course, on the acoustic properties of the propagating and scattering media.

Knowledge of the frequency f_c at which the f^4 - law takes over, combined with ideas about the scattering medium (soft animal tissue, skeleton, swim bladder) can then tell us the approximate size of the individual scatterers.

If the receiver is approximately non-directional near f_c , we have no trouble recognizing this frequency: The echo - corrected for the frequency response of the apparatus - simply falls off as f^4 below f_c . With a directional receiver this fall-off point may be obscured by the frequency-dependence of the directivity function, but the discussion of section IV and the method of analysis of section V take account of this.

What complicates the problem is that - contrary to assumption (7) of section II - distributions in nature *do* have horizontal structure. Sharp peaks appear on the records which are due either to individual scatterers or to localized patches of them. The higher the frequency of observation (the greater the directivity of the receiver, the narrower the field of "view"), the "spikier" the echo traces look, and the worse our averaging over volume elements becomes as a method of analysis. The apparent advantage of better resolution is offset by the indeterminacy restored by the failure of assumption (7): We do not know where the resolved individuals are; specifically, at what angle to the receiver axis they lie. The frequency-dependence of a single echo-peak tells us nothing about the frequency-dependence of the scattering, since we do not know what angle θ to put into the directivity function $b(\theta)$.

On the records are many instances where peaks appearing at a low frequency are not present at higher frequencies. Unfortunately, these permit two interpretations: (a) Low frequency resonances. These would be strong if due to air bubbles (swim bladders). (b) The scatterer is located off the receiver axis and only comes into "view" at low frequencies, where the receiver is less directional.

Present techniques cannot remove this ambiguity. At least two observations on a single scatterer are needed to determine its θ . One might make simultaneous observations with two receivers of different size, or with two receivers differently oriented, or at different locations.

Another ambiguity in the interpretation of single echo-peaks might be pointed out here. This is due to the failure of assumption (4) of section II: There are interference effects, giving rise to fluctuations in echo intensity. If we consider a narrow frequency band, each echo signal is a sinusoid. Echoes from different scatterers come in with random phases and superpose. The fluctuations due to this randomness may have the same appearance as resolved echo-peaks from individual scatterers. If the number N of such (coherent) interfering signals is large, the Law of Large Numbers applies: The relative deviation is equal to $N^{-1/2}$ and therefore negligible.

But interference of two or three echoes can cause sizeable fluctuations : The relative deviation for the sum of two sinusoids of equal amplitude and random phase is equal to $\sqrt{2}$.

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REFERENCES

- ANDERSON, V. C. (1950), Sound scattering from a fluid sphere, *J. Acous. Soc. Amer.*, **22**, 426-431.
- ARONS, A. B. (1954), Underwater explosion shock wave parameters at large distances from the charge, *J. Acous. Soc. Amer.*, **26**, 343-346.
- HERSEY, J. B. and BACKUS, R. H. (1954), New evidence that migrating gas bubbles, probably the swim bladders of fish, are largely responsible for scattering layers on the continental rise south of New England, *Deep-Sea Research*, **1**, (3), 190-191.
- HERSEY, J. B., JOHNSON, H. R. and DAVIS, L. C. (1952), Recent findings about the deep scattering layer, *J. Mar. Res.*, **11**, (1), 1-9.
- JAHNKE, E. and EMDE, F. (1945), *Tables of Functions*, (Dover Publications), **24**.
- MORSE, P. M. (1948), *Vibration and Sound*, McGraw-Hill, (Second Edition).
- UNIV. CAL., DIV. WAR RES. (1946), Stratification of sound scatterers in the ocean, UCDWR File Report No. M397. Unpublished manuscript.

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Regeneration of nutrients in sediments of marine basins*

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Abstract—To assess the extent and significance of nutrient regeneration in marine sediments, the depth distribution of nitrogen, phosphorus and silicon in three basin sediments and their overlying waters were determined. The data obtained were interpreted on the assumption that in a relatively constant depositional environment steady state conditions exist and therefore the change of a property with depth of burial is a measure of the change of the property with time in an isolated mass of sediment. The three sediments differ in pH, Eh, organic matter content and other properties, and it was possible to correlate some of the regeneration processes with the biological and physical-chemical environments.

The nitrogenous part of organic matter deposited in the basin sediments is partially regenerated as ammonia that becomes oxidized to nitrate in sediments of positive Eh and in the overlying water. Phosphate regeneration occurs most intensively in anaerobic sediment; locally net deposition occurs in aerobic sediments of low pH. Dissolved silicate increases with depth in all the sediments. Water immediately overlying the sediment surface is enriched in these nutrients where regeneration in the sediment is active. The return of nutrients from sediment to water is less than 1 per cent of the annual use by phytoplankton.

Calculations show that in one basin a minimum of 1.6 μg -atoms of ammonia per cm^2 of sediment surface pass into the basin water annually. At this rate of regeneration the basin water must be renewed from the open ocean in a period of less than twenty years to maintain existing concentrations of nitrate. Calculations based on an oxygen balance for the sediment and water require renewal in about two years. These results indicate a much more rapid circulation of basin water than had been generally suspected.

INTRODUCTION

THE development of all life depends directly or indirectly on the availability of certain plant nutrients. For marine life, the ultimate source of these nutrients is provided by run-off from land areas although cyclic regeneration of nutrients is necessary to maintain the crop level. Using existing information on the distribution of nitrogen and phosphorus and the general pattern of water movement, RILEY (1951) showed that most regeneration occurs near the top of the water column. Some additional regeneration takes place in deeper water layers, at the bottom, and within the sediment. The general decrease in organic matter with depth of burial in sediments suggests that much of it is decomposed, reforming nutrients. Such regeneration can affect the productivity of the ocean only to the extent that the nutrients are released into the overlying water.

The processes by which the decomposition is effected may involve animal metabolism in part, but they ultimately must require the activities of bacteria, which are known to be abundant in the upper sediment layers. Details of the cycles of nutrients in environments such as soils have been fairly completely characterized and the particular bacteria and the general features of the chemical processes are well known. Although less study has been given to these cycles in the marine environ-

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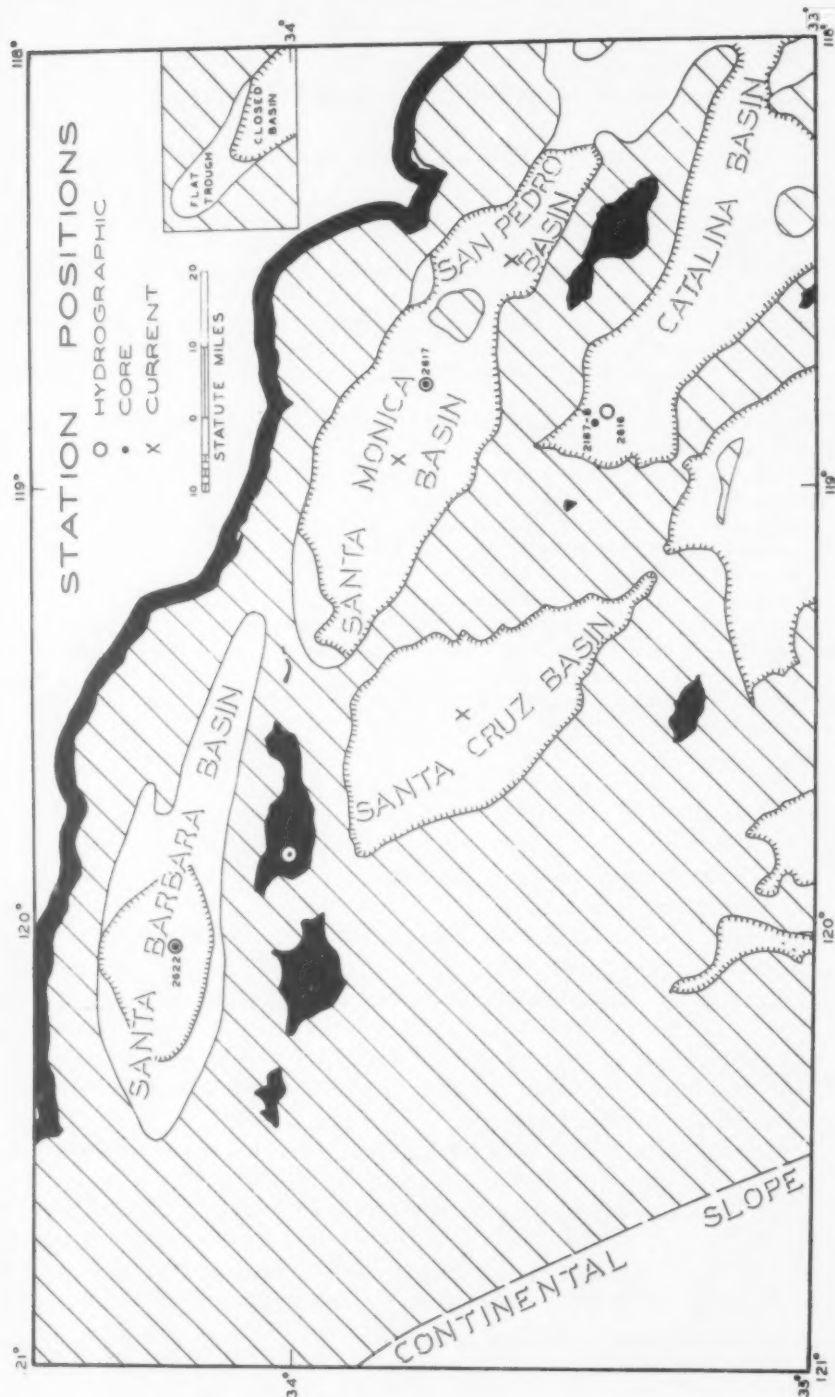


Fig. 1. Positions of water and sediment samples.

ment, it is apparent that they are very similar in many respects to those of soils. As has been discussed more fully elsewhere (EMERY and RITTENBERG, 1952), the type, rate, and extent of bacterial activity in sediments depends on various environmental factors such as oxygen content, hydrogen ion concentration (pH), oxidation-reduction potential (Eh), and temperature, and these factors in turn are modified by bacterial activity. Thus, nitrification and sulphate formation should occur mainly in the top layers of sediment where dissolved oxygen is present, whereas denitrification and sulphate reduction should be limited to the anaerobic sub-surface layers.

The problem to which we have set ourselves is to turn this general picture into a quantitative one for a particular sedimentary environment, restricting the work to the regeneration of nitrogen, phosphorus, and silicon in basin sediments. Data from cores and overlying water were interpreted on an assumption of steady state conditions, i.e., in a relatively constant environment the study of the change in a property with depth of burial is essentially the same as a study of the alteration of the property with time in an isolated mass of sediment. Thus, the activity of bacteria was judged from the stratigraphic viewpoint of their long term effect on the sediments, rather than from the laboratory viewpoint of relatively brief experiments.

Appreciation is expressed to Captain Allan Hancock for providing ship time and laboratory facilities for this project.

ENVIRONMENT OF THE BASINS

Water

In the area off southern California are thirteen well-surveyed closed basins that have an average area of 1,300 km², an average bottom depth of 1,650 m, and an average sill depth of 1,230 m. The sill and bottom depths of individual basins range from one-third to five-thirds the average depths, and in general both are progressively deeper toward the south.

Water in each basin is isothermal and within 0.3°C of the temperature at the sill. Because of differences in sill depths, the water temperature in the basins ranges from 2.5°C in the southernmost basin having the deepest sill to 6.3°C in the northernmost basin with the shallowest sill. The distribution of temperature is such that the waters must have entered each basin at or near its sill depth and consequently have flowed from basin to basin in a general northwesterly direction (EMERY, 1954).

The maximum oxygen content of the basin water is that of the water which enters the basins at or near their sill depths (Figs. 1 and 2). Where the sill is at the depth

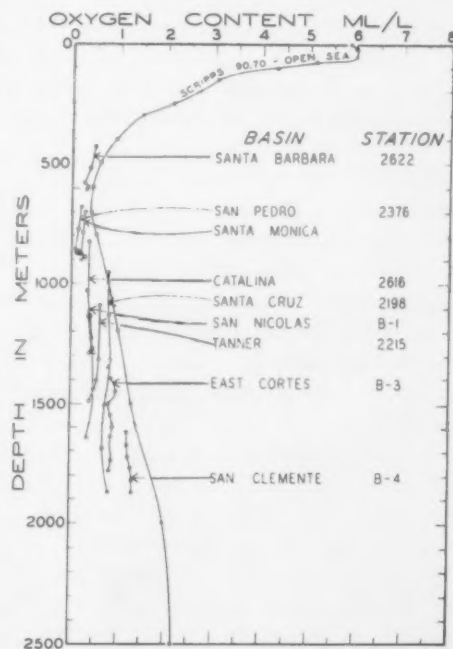


Fig. 2. Oxygen-depth curves for open sea and basin waters. The arrows indicate the sill depths.

of the oxygen minimum of the open sea, 500 to 800 m, the maximum oxygen content is less than about 0.5 ml/L. In general, the deeper the sill depth is below 800 m, the higher the oxygen content. At the very bottom of the basins there exist irregularities in the oxygen content (Table 1) that probably are greater than the error of analysis. Within the basins the oxygen ranges between 1 and 7 per cent of the surface saturation value. The odour of hydrogen sulphide was not detected in any of the water samples.

Sediment

The floors of the basins are fairly flat and consist of sediments that have a thickness of as much as 3,000 m. These sediments are largely composed of materials from two sources: detrital clay, silt, and sand derived from the shore by streams, waves, and wind, and materials of biological origin consisting of calcareous and siliceous skeletal structures and organic matter. The bulk of the biologically derived material is from plankton.

One of the most important constituents of sediment with respect to diagenesis is the interstitial water. If the sediment is uniform in grain size with depth, the water content presents an almost hyperbolic decrease from the surface downward. This decrease of water content with depth is the result of compaction, and the water that is squeezed out must escape upward through the sediment. Owing to continued deposition of sediment, the interstitial water that is forced to move upward never escapes from the surface except by channelling (EMERY and RITTENBERG, 1952).

Benthonic organisms

Metazoans are scarce on the floors of the San Pedro and Santa Monica Basins and very abundant in the Catalina Basin (HARTMAN, 1955; EMERY, 1952). The abundance parallels the oxygen concentrations. Metazoans play a dual role in the destruction of organic matter and regeneration of nutrients. In addition to their primary scavenging function, some of the larger animals constantly turn over and mix the sediment to a limited depth. This activity contributes to processes that bring many thousands times more oxygen into contact with the organic matter than was present in the original interstitial water (EMERY and RITTENBERG, 1952).

In spite of renewal of oxygen, bacteria within the sediment of some basins exhaust the free oxygen within a brief time (short depth of burial) as shown by a change from positive to negative Eh. After all free oxygen is used some bacteria are able to utilize the oxygen in dissolved sulphate, as is indicated by the decrease in sulphate-chloride ratio with depth and by the presence of hydrogen sulphide (Table 2). Bacteria are abundant in the surface sediments and their numbers decrease with depth. Numerous investigations have shown that the various species responsible for the important biochemical processes are essentially universally distributed in all types of sediment. Their detection in a particular sediment unfortunately does not prove that they are active *in situ*. Consequently, their further detection and enumeration contributes little to an understanding of the processes occurring in a particular sedimentary environment.

Choice of basins for study

Three basins were selected for study of regeneration of nutrients, largely on the

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Fig. 3. Bottom water sampler on deck with designer, Mr. ALEX CAMPBELL. Two of the four sample chambers are shown, the bottom one with valves open and the second one with valves closed. Valves are open during lowering to permit flow of water through the chambers. On contact with the bottom the disk-like foot pushes a thin rod upward, releasing the valves so that they can be pulled shut by springs within the chambers.

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basis of the Eh of their sediments: Santa Barbara, Santa Monica, and Catalina (Fig. 1). Sediment in Santa Barbara Basin has a negative Eh, a strong odour of hydrogen sulphide, and presumably no free oxygen from the surface to the maximum depth in the core, 2 m (Table 2). In Santa Monica Basin the sediment has an Eh that varies from slightly positive to slightly negative, no hydrogen sulphide, and presumably some free oxygen to the same depth. Finally, both kinds of environments are combined in Catalina Basin in which the sediments characteristically have positive Eh from the top to 1 m, below which the Eh is negative. Hydrogen sulphide is absent at the top and its odour increases from weak at 1 m to strong at 2 m. These characteristics were similar in each of 4 to 8 cores taken in each of the basins.

The sediment of Santa Barbara Basin is fine mud. That in Santa Monica Basin is silty mud containing layers of sand as thick as 10 cm. Again Catalina Basin is intermediate, consisting of fine mud with 3 or 4 layers of fine sand as much as 5 cm thick between the surface and 2 m. Calcium carbonate in sediment of the three basins averages 17, 10, and 22 per cent, respectively. Organic matter at the top averages 7.0, 3.0, and 5.5 per cent respectively, and decreases with depth.

In beginning stages of this study, several preliminary cores and water samples from San Pedro and Catalina Basins were analyzed. When methods of analyses were improved, new samples were collected and the less complete early results discarded, although they did not differ materially from the later results.

ANALYTICAL METHODS

Basin water samples

Sampling—Basin water high above the bottom was sampled with Nansen bottles, but because of the importance attached to the composition of water immediately above the bottom a new device, the bottom water sampler (Fig. 3), was designed and built by Mr. ALEX CAMPBELL, chief engineer of the University of Southern California's research vessel *Velero IV*. With this device water samples were taken at two-foot (0.5 m) intervals just above the bottom. Water for dissolved oxygen determination was drawn directly from the collection apparatus and the reagents added immediately. Samples for other analyses were transferred to polyethylene bottles. Unless otherwise specified measurements were made aboard ship within a few hours after collection.

Oxygen—Dissolved oxygen was determined by the Winkler method, using reagents prepared according to POMEROY and KRISCHMAN (1945).

Hydrogen ion concentration—As soon as the samples approached the air temperature (about 20°C), the pH was measured by means of a Beckman Model G pH meter using the glass electrode (No. 290) and the calomel reference electrode (No. 270).

Phosphate—Phosphate was determined by the colorimetric method of Denigès as modified by ROBINSON and THOMPSON (1948a) using Nessler tubes.

Silicate—Silicate concentration was measured on the samples 2 or 3 days after collection by the procedure of ROBINSON and THOMPSON (1948c).

Nitrate—The concentration of nitrate was estimated by visual comparison of the colour developed after 8 to 10 hours by the reduced strychnine reagent (strychnidine in sulphuric acid) with a set of previously calibrated colour standards which were prepared from methyl orange in N/100 HCl (WATTENBERG, 1937). In most of the samples a dilution with 4 parts of "nitrate-free" sea water was required to obtain a colour intensity which could be estimated to about $\pm 1 \mu\text{g-a/L}$. Independent comparisons by two observers generally agreed to $\pm 1 \mu\text{g-a/L}$, which corresponds to $\pm 5 \mu\text{g-a/L}$ in the undiluted samples.

Chlorinity—The chlorinity of the samples was determined on shore by the standard Knudsen titration method.

Interstitial water samples

Sampling—A 500-kg gravity corer was used to obtain vertical samples 2 m in length and 6 to 10 cm in diameter. As soon as the cores were brought aboard ship they were removed from the core barrel and scraped clean of their smeared outer layer. After the colour, texture, and odour were recorded, the cores were cut into short sections and sealed in glass jars. Within two hours, the pH and Eh of the sections were measured in the manner described by EMERY and RITTENBERG (1952). Separation and analysis of the interstitial water was completed on shore within 2 days after collection. To determine the concentration of constituents in interstitial water, it was necessary to separate the water from the sediment. Since direct filtration, squeezing through filter cloth, or centrifugation is ineffective, dilution methods were used.

Separation Method A—Dilution with distilled water—About 100 gm of wet sediment were weighed and added to a known volume (50 to 150 ml) of distilled water. The mixture was stirred vigorously for about 10 minutes and the water was separated from the sediment by centrifugation and then decanted through a Whatman No. 42 filter. Water content of the original wet sediment was determined by drying a separate sample at 105°C. From the original water content, the weight of wet sediment, and the volume of water added, the dilution factor was determined and the analytical results were calculated to the concentrations in the interstitial water.

Separation Method B—Dilution with sea water—It was realized that distilled water used in method A may dissolve some precipitated or adsorbed material which is not present in the interstitial water *in situ*. Therefore, some samples were treated in the same manner as method A but with selected filtered sea water instead of distilled water. The various determinations were made on the sea water and the concentrations in the interstitial water were corrected for the constituents, thus introduced. For both extraction methods a correction for turbidity was required in all colorimetric measurements.

Data from samples obtained by both methods A and B indicated that the use of distilled water gave concentrations of silicate and phosphate that are 10 to 20 per cent higher than by the use of sea water. Although this difference is appreciable and could be important in some work, either method is regarded as adequate for the present study in which differences in concentration between basin water and interstitial water and relative changes with depth in the latter are more important than absolute values. Determinations of silicate and colorimetric spot-plate estimates for ammonia made on interstitial water obtained by squeezing through filter cloth showed the same concentration range as that found by the dilution methods.

Ammonia—Distillation of ammonia was conducted in a standard micro-Kjeldahl apparatus (NEIDERL and NEIDERL, 1942) after addition of sufficient NaOH to make the sample approximately 0.3 molar. The distillate was collected in N/100 HCl, and the ammonia was measured either by titration of the remaining acid with standard N/100 NaOH or colorimetrically with Nessler reagent, depending on its concentration.

The possibility of formation of ammonia by hydrolysis of organic nitrogen compounds during the distillation from the hot alkaline solution was considered. It was found that the yield of ammonia did not change upon increasing the distillation time from 5 to 15 minutes, suggesting that little ammonia is contributed in this manner and that the nitrogen compounds are probably only very slowly hydrolysed.

Nitrate—Two methods were used for the estimation of the nitrate concentration. The first was a reduction method adapted from the one reported by SZABO and BARTHA (1951), essentially as described by VARNER, BULEN, VANECKO and BURRELL (1953).

The second procedure was a direct colorimetric estimation of nitrate by the method used for basin waters. This was employed on Cores 2617 and 2622, where nitrate was low or absent. It was not entirely satisfactory owing to an interfering yellow colour. Both methods of analysis gave comparable results in experiments with interstitial water samples to which known amounts of nitrate were added.

Nitrite—The nitrite concentration was determined by the conventional oceanographic method (ROBINSON and THOMPSON, 1948b), using smaller samples and a Coleman spectrophotometer.

Phosphate—Phosphate analyses were made as in the basin waters, using appropriately diluted samples. Salt effect corrections were not applied because the chlorinity was kept above 17‰, and in most cases about 19‰, by the use of a sodium chloride solution for the sample dilutions.

Silicate—The silicate concentration also was determined by the method given for the basin water except for the necessary dilutions which were made with silicate-free distilled water. No salt effect corrections were applied.

Sulphate/Chloride ratio—The chloride concentration was measured by the Mohr titration method and the sulphate gravimetrically as barium sulphate on samples obtained by method A. The ratio of sulphate to chloride for a sample of surface sea water was found to be 0.1390, which is in close agreement with the accepted ratio of 0.1395 (THOMPSON, JOHNSON and WIRTH, 1931).

Dried sediment samples

Organic nitrogen—The total nitrogen in the sediments was measured by the standard micro-Kjeldahl method (NEIDERL and NEIDERL, 1942) on samples which were dried at 105°C. The determinations include particulate and soluble organic nitrogen as well as any nitrite and nitrate in the sediments. Part or all of the ammonia is lost during the drying process and consequently the Kjeldahl nitrogen is slightly lower than the total *in situ* value. Considering the relative abundance of the various nitrogen compounds in sediments, however, the Kjeldahl value can be taken as essentially equal to the organic nitrogen content.

Total phosphorus—Total phosphorus was determined by the method of SHERMAN (1942) which was developed for analysis of soils and circumvents the difficulty introduced by the rather high concentrations of iron in the sediments.

NITROGEN

Basin water

The nitrate concentration below the sills of the basins is very uniform, averaging about 35 $\mu\text{g-a/L}$ in the Catalina and Santa Monica Basins and 40 $\mu\text{g-a/L}$ in the Santa Barbara Basin. These values correspond to the nitrate concentrations in the waters just above the sill of each basin. The nitrate concentration in the bottom-most water was lower in the Santa Barbara Basin, the same in the Santa Monica Basin, and higher in the Catalina Basin, as compared to the rest of the basin water. Correspondingly, the interstitial water in the top of the cores contained no, low, and very high nitrate, respectively. The differences noted in the lowest samples of basin water are not great, and considering the difficulties inherent in the analytical method may not be significant. However, the data do suggest an influence of the interstitial water on the bottom water composition, a view supported by the nitrite and phosphate distribution.

Nitrite was present in low concentrations in the water just above the sediment surface of the Catalina and San Pedro Basins, but was absent in the rest of the water of these basins. The ammonia concentration was too low to be measured by the method of analysis used for interstitial water. It is known from previous work (SVERDRUP, JOHNSON and FLEMING, 1942, pp. 243-244) that ammonia concentration in deep water is less than 2 $\mu\text{g-a/L}$, but unfortunately its distribution just above the sediment surface has not been explored.

Sediment

Nitrate and nitrite—Nitrate was found in the interstitial waters of the upper layer of sediment in the Catalina and possibly in the Santa Monica Basins, but it was absent in the Santa Barbara Basin sediment. Its concentration in the Catalina Basin sediment, 240 $\mu\text{g-a/L}$, is much higher than in the overlying basin water and is roughly six times the maximum reported for sea water; it is apparent that nitrification is active here. In the other two basins the nitrate concentration in the upper layer

Table 1, *Composition of Basin Waters.*
 AHF 2616, Catalina Basin, 31 March 1954, Lat. 33°24', Long. 118°50'.

Depth (m)	Depth (ft)	Temp. (°C)	Cl. (‰)	pH	O ₂ (ml/L)	NO ₂ -N (μg-a/L)	NO ₃ -N (μg-a/L)	PO ₄ -P (μg-a/L)	Si (μg-a/L)
0	0	13.6	18.40	8.28	5.60	0.2	0	0.3	
200	657	8.65	18.85	7.84	1.23		30	3.0	65
354	1160	7.09	18.93	7.71	0.67	0.0	40	3.0	92
504	1652	5.93	18.96	7.67	0.35		40	3.0	114
679	2226	5.18	18.99	7.67		0.0	35	3.0	127
831	2727	4.28	19.02	7.69	0.37		35	3.0	160
982	3222	Sill							
990	3250	4.16	19.04	7.70		0.0		3.0	165
1143	3749	4.02	19.04	7.73	0.37		35	3.0	165
1274	4178	4.01	19.04	7.70	0.45		35	3.0	168
1283.7	4212	4.02*	19.05	7.82	0.45		35	3.0	168
1284.2	4214	4.02	19.01	7.89			40		155
1284.7	4216	4.02	19.06	7.80	0.46		35	3.0	165
1285.3	4218	4.02	19.06	7.80	0.31		35	3.0	165
1285.8	4220	4.02	19.06	7.79	0.49		35	2.6	165
1286.4	4222	4.02	19.06	7.80	0.46	0.0	40	2.8	163
1287.0	4224	4.02	19.07	7.80	0.42	0.0	35	3.0	167
1287.5	4226	4.02	19.06	7.79	0.39	0.05	45	3.6	163
1288	4228	4.05	Bottom	7.72					

AHF 2617, Santa Monica Basin, 1 April 1954, Lat. 33°45', Long. 118°46'

0	0	13.4	18.44	8.26	5.77		0	2.3	
274	900	7.83	18.90	7.77	1.30		40	2.8	
427	1400	6.66	18.94	7.73	0.69		40	3.0	
579	1900	5.70	18.99	7.70	0.37		40	3.2	
701	2300	5.35	18.99	7.69	0.23	0.0	35	3.2	
737	2418	Sill							
792	2600	5.14	19.00	7.68	0.30	0.0	35	3.2	
884	2900	5.08	19.01	7.69	0.20		30	3.2	
894.4	2934	5.05	19.01	7.71	0.23		35	3.2	
895.0	2936	5.05	19.01	7.74	0.19		35	3.2	
895.6	2938	5.05	19.00	7.74	0.24			3.4	
896.2	2940	5.05	19.01	7.73	0.22		35	3.5	
896.8	2942	5.05	19.01	7.76	0.32		40	3.3	157
897.4	2944	5.05	19.02	7.76	0.22	0.0	40	3.3	156
898.0	2946	5.05	19.02	7.76	0.23	0.05	35	3.4	159
898.5	2948	5.05	19.02	7.77	0.19	0.10	35	5.2	
899	2950	Bottom				0.10			

AHF 2622, Santa Barbara Basin, 11 April 1954, Lat. 34°13', Long. 120°02'

0	0	12.1	18.50	8.29	5.01		9		
61	200	9.13	18.67	7.90	2.38		35	2.1	46
137	450	8.86	18.83	7.76	1.33		40	2.3	64
221	725	8.00	18.89	7.74	1.01		40	2.7	76
433	1420	6.99	18.90	7.70	0.48		40	3.0	102
475	1560	Sill							
524	1720	6.49	18.91	7.84	0.36		40	3.1	120
585	1920	6.26	18.93	7.88	0.24			3.1	144
598.2	1963	6.26	18.93	7.94	0.35		40	2.9	130
598.7	1965	6.26	18.97	7.88	0.33		40	3.0	122
599.2	1967	6.26	18.95	7.79	0.30		40	3.1	126
599.7	1969	6.26		7.95			30	4.4	172
600	1970	Bottom							

* Italicized values are based on earlier data. Nitrite values given for Santa Monica Basin were taken from the oceanographically similar San Pedro Basin.

Table 2. *Composition of Cores.*
 AHF 2187-2188, Catalina Basin, 25 November 1953, Lat. 33°25', Long. 118°52'.

Depth (cm)	Water (% dry wt.)	pH	Eh (mv)	H ₂ S (odour)	SO ₄ /Cl	N (%)	P (%)	Interstitial water from core				
								NH ₃ -N (μg-g/L)	NO ₂ -N (μg-g/L)	NO ₃ -N (μg-g/L)	PO ₄ -P (μg-g/L)	Si (μg-g/L)
0-2*	200	7.60	+ 205	none		0.50	0.087	450	4.4	240	18	760
2-8	175	7.77	+ 165	none		0.52	0.086	170	6.0	35	16	780
18-23	136	7.70	+ 275	none		0.43	0.092	260	2.7	95	18	530
38-43	122	7.70	+ 308	none		0.39	0.073	280	2.0	44	23	730
64-69	109	7.83	+ 257	strong		0.36	0.072	340	0.0	89	22	980
79-84	111	8.42	- 50	strong		0.32	0.069	430	0.0	21	16	1200
94-99	107	8.20	- 55	strong		0.27	0.069	580	0.0	34	18	1120
114-131	97.5	8.05	- 128	strong		0.26	0.077	1200	0.0	23	46	2030
158-169	61.6	8.26	- 149	strong		0.13	0.083	1900	0.0	12	100	1690
191-203	61.8	8.25	-	strong		0.15	0.085	3800			140	1380

Table 2 (continued)
 AHF 2617, Santa Monica Basin, 1 April 1954, Lat. 33°45', Long. 118°46'.

Depth (cm)	Water (% dry wt.)	pH	Eh (mv)	H ₂ S (odour)	SO ₄ /Cl	N (%)	P (%)	Interstitial water from core				
								NH ₃ -N (μg-g/L)	NO ₂ -N (μg-g/L)	NO ₃ -N (μg-g/L)	PO ₄ -P (μg-g/L)	Si (μg-g/L)
0-10	270	7.65	+ 25	none		0.426		510	1.2	6?	8.0	540
10-25	115	7.71	+ 20	none	0.137	0.158	0.114	710		6?	5.5	
25-41	96.2	7.66	+ 5	none		0.202		1200	0.0	0	6.5	1400
41-53	66.7	7.64	+ 30	none								
53-61	41.8	8.02	+ 30	none		0.068		2700		0	3.1	
61-69	24.1	7.96	0	none		0.181		4900	0.0	0		
69-84	85.2	8.05	+ 10	none	0.129	0.071	0.121	3000		0	4.0	1100
84-99	81.6	7.56	0	none								1100
99-114	78.0	7.73	- 5	none		0.119		5500	0.0	0	16.5	1300
114-130	64.1	7.81	- 55	none								
130-143	72.5	7.88	- 30	none	0.113	0.000		5100		0	6.6	
143-155	56.0	7.84	+ 25	none								
155-168	41.5	7.88	- 5	none		0.084	0.104	7300	0.0	0	1.6	940
168-182	31.1	7.86	+ 10	none		0.049		6100		0	8.0	
182-196	28.4	7.95	- 45	none		0.033		4400	0.0	0	1.4	

Table 2 (continued)
AHF 2622E, Santa Barbara Basin, 11 April 1954, Lat. 34°13', Long. 120°02'.

Depth (cm)	Water (% dry wt.)	pH	Eh (mv)	H ₂ S (odour)	SO ₄ /Cl	N (%)	P (%)	Interstitial water from core				
								NH ₃ -N (µg-a/L)	NO ₂ -N (µg-a/L)	NO ₃ -N (µg-a/L)	PO ₄ -P (µg-a/L)	Si (µg-a/L)
0-1	669	7.95	—	strong	—	0.290	—	610	—	0	3.2	—
1-15	328	8.25	280	strong	—	0.344	—	560	0.1?	0	43	—
15-30	206	8.25	305	strong	0.088	0.336	0.102	1800	0.5?	0	50	—
30-46	182	8.25	320	strong	—	0.347	—	2900	—	0	56	—
46-61	186	8.20	320	strong	0.043	—	—	—	—	0	65	1800
61-76	177	8.00	320	strong	—	—	—	—	—	0	85	—
76-91	184	8.15	315	strong	0.043	0.317	0.099	3500	0.1?	—	—	1700
91-107	155	8.22	345	strong	—	0.314	—	4800	—	0	122	—
107-122	156	8.05	335	strong	—	—	—	—	—	—	130	2000
122-137	151	8.23	320	strong	—	0.290	—	6100	—	0	180	—
137-153	135	8.20	310	strong	0.004	—	—	—	—	—	—	2300
153-168	132	8.45	300	very strong	—	0.271	0.087	8700	—	0	160	1900
168-183	124	8.25	305	very strong	—	—	—	—	—	0	179	—
183-198	112	8.20	295	very strong	—	0.218	—	11400	—	0	194	—

* Core depths are not corrected for the approximately 50% shortening that occurs when the core barrel is driven into the bottom.

of sediment is less than that of the overlying water, showing not only that nitrification is not occurring but that an opposite process is removing the nitrate initially present in the water laid down with the sediment. These findings correlate perfectly with the Eh data that show highly oxidizing conditions in the upper Catalina Basin sediments and semi-reducing or strongly reducing conditions at the surface of the other two sediments. Nitrification, being an obligatory aerobic process, thus, cannot occur in the latter two sediments.

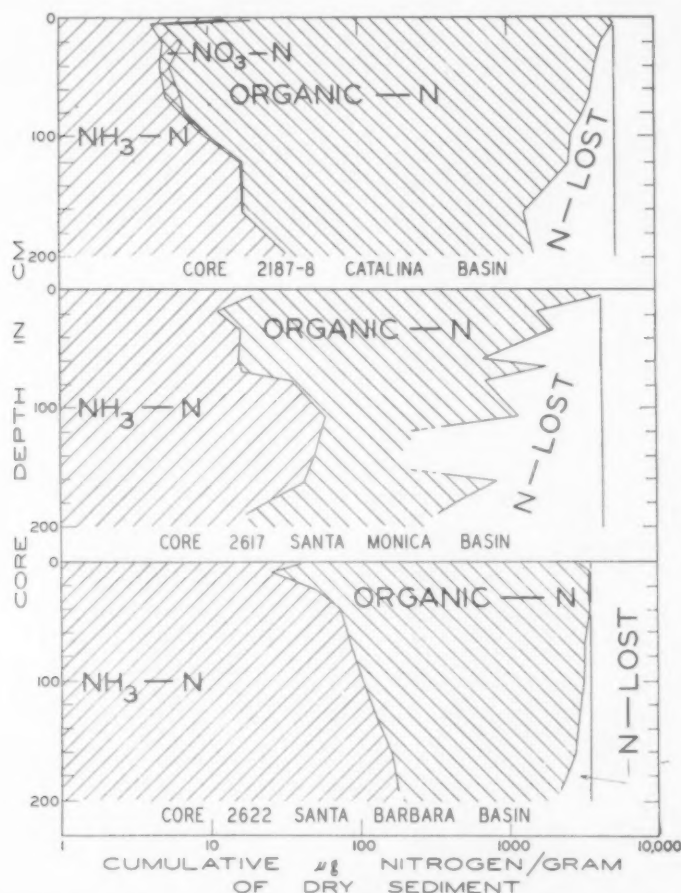


Fig. 4. Concentration of nitrogen compounds with depth in basin sediments. Note logarithmic scale.

In the Catalina Basin sediment the nitrate concentration of the interstitial water decreases markedly, although somewhat erratically, with depth. Nitrification must therefore be limited to the upper layer of sediment and the nitrate that is formed must be reduced during further burial of the sediment. Nitrite also decreases with depth in this sediment and its concentration drops to zero at a level where appreciable nitrate is still present; consequently, it cannot be the final product of nitrate reduction.

Nitrite, in low concentration, was also found in the top layer of the Santa Monica Basin sediment and was absent in the lower layers.

Ammonia—Ammonia was present in relatively large amounts in the interstitial waters of all three sediments. The lowest concentration found, $170 \mu\text{g-a/L}$, is roughly 50 times as great as the maximum reported for sea water, and the highest, $11,400 \mu\text{g-a/L}$, roughly 3,000 times as great. BRUJEWICZ and VINOGRADOVA (1946) also found much greater concentrations of ammonia and other nutrients in interstitial water than in overlying water of the Caspian Sea.

The ammonia concentration increases with depth of burial in the sediments of both the Catalina and Santa Barbara Basins, indicating that bacterial activity in both sediments occurs at least to the depth of coring. Qualitatively reflecting this increase is the decrease with depth of organic nitrogen in both sediments. Quantitatively, there is a greater accumulation of ammonia with depth in the sediment of the Santa Barbara Basin as compared to that of the Catalina Basin, whereas the decrease in total nitrogen is much greater in the latter sediment. Ammonia also increases with depth in the Santa Monica Basin sediment but its concentration below 53 cm shows marked fluctuations.

Organic nitrogen—The relation between organic and inorganic forms of nitrogen is shown in the logarithmic plot (Fig. 4). Organic nitrogen predominates at all depths and constitutes 90 per cent or more of the total. The amount of organic nitrogen decreases with depth in all three sediments, the bottom-most layers of the cores containing 92, 70, and 35 per cent less than the surface layer in the Santa Monica, Catalina and Santa Barbara Basin sediments, respectively.

The organic nitrogen-depth curves for the Catalina and Santa Barbara Basin sediments show a fairly regular decrease, whereas the curve for the Santa Monica Basin sediment has marked fluctuations. Similar fluctuations exist in the ammonia, phosphate, and silicate content of this sediment. Much of the variability in these properties is undoubtedly due to the non-homogeneous nature of the Santa Monica Basin sediment, in which layers of markedly different grain sizes and water contents are present.

An inspection of Fig. 4 shows that the accumulation of inorganic nitrogen, predominantly or exclusively in the form of ammonia, does not balance the decrease in organic nitrogen. The difference between these two quantities represents nitrogen escaped from the sediment and/or molecular nitrogen, a form not detected by the Kjeldahl method. The lost nitrogen is indicated by the unshaded areas of Fig. 4, and it is apparent that the loss is appreciable in all three sediments.

If one knew the quantity of molecular nitrogen formed, then a value for the fixed nitrogen that escapes from the sediment to the water could be determined. A consideration of the nitrogen cycle and the basin environments shows that this is possible for at least one basin.

Nitrogen cycle

Ammonia is the first inorganic product in the regeneration of organic nitrogenous materials by microorganisms. Its liberation can occur aerobically or anaerobically and thus its formation is independent of the Eh of the environment. Ammonia, in turn, is oxidized to nitrite and nitrate by a specific group of bacteria, the *Nitrobacteriaceae*, obligate aerobic forms that cannot nitrify in reducing environments.

Recently, evidence for the direct nitrification of organic compounds by heterotrophic bacteria has been presented (see for example, JENSEN, 1953). The quantitative importance of direct nitrification of organic compounds in nature is uncertain, but in any event the process is an aerobic one and no biological mechanism for nitrification under anaerobic conditions is known.

Nitrate, and to a lesser extent nitrite and ammonia, is used for the production of new plant material, thus completing the cycle. However, nitrate and nitrite in the proper environment and in the presence of the proper facultative or anaerobic bacteria can be denitrified with molecular nitrogen as the end product. The denitrification process is inhibited by molecular oxygen and consequently occurs only in an anaerobic environment. No biological processes have been described by which molecular nitrogen is formed directly from ammonia or from organic nitrogen. Molecular nitrogen can arise by abiogenetic reactions: i.e., amino acids, amines, and ammonia react spontaneously with nitrite at low *pH* to form nitrogen. Reaction rate computations based on extrapolations from the data of DUSENBERRY and POWELL (1951) as well as calculations by COOPER (1937) show that abiogenetic formation of nitrogen is unimportant in the marine environment. In any case, here also an oxidized nitrogen compound, nitrite, is required. Thus, no method for the formation of nitrogen in the absence of an oxidized nitrogen compound is known.

From the Eh measurements one would predict that nitrification is possible in the upper layers of the Catalina Basin sediment but not in the Santa Barbara Basin sediment; the distribution of nitrate in the two sediments bears out this prediction. Also on the basis of the Eh data, denitrification can occur in the sub-surface layers of the Catalina Basin sediment and from the surface downward in the Santa Barbara Basin sediment. It is possible that denitrification can also occur in the upper layer of the Catalina Basin sediment if differences in micro-environment exist from point to point, i.e., small reducing areas may exist in a macro-environment of positive Eh. The chemical data (Table 2) coincides with what is expected from the above considerations.

Since nitrification does not occur in the Santa Barbara Basin sediment, the amount of molecular nitrogen that could be produced should not exceed the initial small amount of nitrate and nitrite present in the basin water trapped with the sediment. This quantity is inconsequential as compared to the nitrogen lost from the sediment (Fig. 4). Consequently, the nitrogen deficit can be assumed to be equal to the ammonia returned to the overlying water, and the effective amount of nitrogen regeneration can be calculated on this basis. Whether dissolved organic matter escapes is unknown. The same calculation cannot be made for the Catalina Basin since it is not known what fraction of the nitrogen deficit goes to molecular nitrogen.

Rate of escape of ammonia from sediment of Santa Barbara Basin

On the assumption that the downward decrease of organic nitrogen is entirely the result of its conversion to ammonia, the annual enrichment of overlying water in nutrient nitrogen can be computed from the difference between the decrease in organic nitrogen and the ammonia found in the sediment. The results of such computations for Core 2622 are presented in Table 3.

Shortening of the sediment during coring operations is produced by the down-bowing and corresponding thinning of sediment layers in advance of the open end

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of the core barrel. As shown by EMERY and DIETZ (1941) this shortening results in an average core-length to penetration ratio of 51 per cent for sediments like those of Santa Barbara Basin.

For simplicity we may take the *in situ* thickness of sediment layers as twice that of their thickness in the cores; this is the only portion of the report that is based on computed *in situ* depths rather than depths in the cores. The average water content of 100 cm zones of *in situ* sediment were estimated from a smooth curve drawn from water content data of Core 2622. Using these values for water content, an assumed rate of deposition of 0.091 gm dry weight per cm² (EMERY and RITTENBERG, 1952), and a grain density of 2.60, we find that the thickness of annual layers of sediment range from 0.211 cm at 50 cm *in situ* depth to 0.143 cm at 350 cm depth. These thicknesses correspond to a time span of 475 years for deposition of sediments

Table 3.
Ammonia Budget of Core 2622

Core depth - cm	In situ depth - cm	Average water content - percentage dry weight	Average thickness of annual layer - cm	Time span of zones - years	Volume of water in 1 cm ² column - litres	Decrease of organic nitrogen - percentage N	Total conversion of Nitrogen in 1 cm ² column - μ -atoms	Ammonia-Nitrogen present in water - μ -g/L	Total ammonia-nitrogen in 1 cm ² column - μ -atoms	Converted organic-nitrogen minus ammonia-nitrogen in 1 cm ² column - μ -atoms	Escaped ammonia-nitrogen from 1 cm ² column - μ -atoms/year
0-50	0-100	198	0.211	475	0.0834	0.015	230	2000	170	60	0.13
50-100	100-200	176	0.190	525	0.0816	0.022	370	3700	300	70	0.13
100-150	200-300	149	0.167	600	0.0790	0.035	680	5800	460	220	0.37
150-200	300-400	122	0.143	700	0.0755	0.062	1410	10,000	750	660	0.94
				2300							1.57

in the top 100 cm depth zone and 700 years for sediments now between depths of 300 and 400 cm. The nitrogen that has been converted to ammonia from each 100 cm depth zone of a 1 cm² column is the product of the dry weight of each annual layer (0.091 gm) times the percentage decrease of organic nitrogen (0.015/100 in the 0-100 cm zone) times the number of years divided by 2. Expressed in μ -g-atoms the converted nitrogen ranges from 230 for 0-100 cm to 1,410 for 300-400 cm.

As computed from the concentration of ammonia in the water and the volume of water in 100 cm zones of the 1 cm² column, the ammonia that remained in the sediment ranges from 170 μ -g-atoms for the 0-100 cm zone to 750 for 300-400 cm. Thus, approximately two-thirds of the ammonia-N remained in the interstitial water and one-third escaped. Pro-rating the escaped one-third over the number of years

represented by each depth zone, we find that the greatest escape occurred from the zones having the highest concentration of ammonia.

The total annual escape of ammonia from the 400 cm column is $1.6 \mu\text{g-atoms}$. In other words, each year there escapes from each square cm of sediment surface in the Santa Barbara Basin $1.6 \mu\text{g-atoms}$ of ammonia derived from the top 400 cm of sediment plus an unknown additional amount from greater depths. Assuming its oxidation to nitrate in the overlying water, this amount of ammonia-nitrogen equals the amount of nitrate-nitrogen present in 45 cm^3 of sea water. The ammonia-N released is only about 0.4 per cent of the annual use of nitrogen by phytoplankton in the region (SVERDRUP, JOHNSON and FLEMING, 1942, pp. 929, 938). The average depth between sill and bottom of this basin is 68 m. In a 1 cm^2 column there would be 6.8 L of sea water. Thus, the sediment liberates ammonia equivalent to all the nitrate in the basin water during a period of $6.8 \times \frac{1000}{45} = 150$ years. Since the concentration of nitrate in the basin water does not exceed that of the open ocean at sill depth ($40 \mu\text{g-a/L}$) by more than $5 \mu\text{g-a/L}$ (the limit of accuracy of analysis), replacement of basin water must occur in less than 20 years.

PHOSPHORUS

Basin water

The bulk of the water in the basins has an essentially uniform phosphate* concentration (3.0 to $3.2 \mu\text{g-a/L}$) coinciding with the concentration in the water just above the sills. The fragmentary data available on the phosphate concentration in deep water of the open ocean in this area show very little change below 300 m, although there is usually a maximum at about 1,000 m followed by a very slow decrease at greater depth. Thus, although the sill depths of the three basins vary from 475 to 982 m, the concentration of phosphate at the sills is about the same.

The water just above the sediment surface contains appreciably more phosphate than that in the rest of the basin. In two of the basins the lowest water sample was taken 0.5 m above the bottom, in the third, about 0.3 m. In all three basins the next samples were 0.5 m higher, and these had the same phosphate content as the water at sill depth. The interstitial waters in the top layers of sediment have a much greater content than the overlying water. Thus, a very sharp gradient exists in the water from just below the sediment surface to no more than a metre above. These data show that regeneration is active in the sediment, and that some phosphate is passing from the sediment into the overlying water. The sharpness of the gradient also suggests that mixing in the basins is sufficient to maintain uniform conditions in all but a thin bottom layer.

Sediment

The phosphate concentration in the interstitial water of the basin sediments ranges up to 50 times the values reported for sea water. The content varies from basin to basin and with depth in the sediment column.

In the Catalina Basin the phosphate concentration remains fairly constant to a depth in the core of 100 cm, averaging $19 \mu\text{g-a/L}$ of interstitial water (Fig. 5). The content increases almost eight-fold in the next 100 cm, reaching $140 \mu\text{g-a/L}$ at 200 cm.

* The word phosphate in this discussion refers only to dissolved orthophosphate; the word phosphorus is used in reference to the total content, dissolved and solid.

In sediment of Santa Barbara Basin the phosphate increases with depth as in the lower half of the core from Catalina Basin, but the increase begins at the surface so that concentrations exceed those of Catalina Basin at all depths. The greatest value, at the bottom of the core, is nearly $200 \mu\text{g-a/L}$. Dissolved phosphate in the sediment of the Santa Monica Basin varies erratically and fails to show a trend towards increasing content with depth like in the other two sediments. Its concentration is much lower than in the other sediments and in several zones it is less than that of the water in the basin.

Total phosphorus in the sediments ranges between 0.069 and 0.120 per cent (dry weight basis) with greatest values where organic content is least (Santa Monica Basin). The average value, 0.094 per cent, corresponds to that of phosphorus in clays and silts reaching the ocean, 0.08 per cent, and is similar to the average for 52 nearshore terrigenous muds, 0.09 per cent, as reported by CLARKE (1924, p. 518). The total phosphorus shows no trend with depth except for the slight decrease in the Santa Barbara Basin which is probably fortuitous due to the small number of samples analysed. In each of the sediments total phosphorus is more than 100 times the amount of dissolved phosphate-phosphorus and therefore the fluctuations in phosphate are small compared to the total.

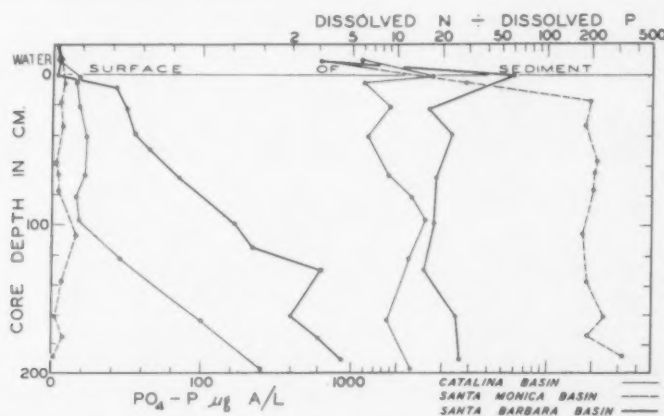


Fig. 5. Variation of phosphate and dissolved nitrogen-phosphorus weight ratio with depth in basin sediments.

The weight ratios of total nitrogen to total phosphorus at the surface of the sediments are 5.8, 3.3, and 1.4, respectively, for the Catalina, Santa Barbara, and Santa Monica Basins. In each basin the ratios decrease with depth in response to the loss of nitrogen and the average ratios are 4.2, 3.2, and 0.9, respectively. The nitrogen to phosphorus ratios at the sediment surface, being lower than that of plankton, 7.2 (SVERDRUP, JOHNSON and FLEMING, 1942, p. 928), are indicative of the abundance of inorganic phosphorus in the material reaching the bottom.

The weight ratio of dissolved nitrogen to phosphate-phosphorus is relatively constant in each sediment, except for the surface sample, showing a parallel between the increase of ammonia and of phosphate with depth (Fig. 5). However, the ratios are markedly different from basin to basin, averaging 10, 20, and 200, respectively, for the Catalina, Santa Barbara, and Santa Monica Basins.

Phosphorus cycle

In contrast to nitrogen, which is supplied almost entirely in the form of organic nitrogen, it can be concluded that the bulk of the phosphorus deposited in the basin sediments is inorganic. Detrital phosphate minerals (e.g., apatite) and phosphate adsorbed on hydrolyzates and oxidates (e.g., clays and ferric hydroxide) probably contribute the bulk of the phosphorus. A smaller percentage is contributed by organic debris and a still smaller amount, less than 0.01 per cent of the total, is from basin water initially trapped within the interstices of the sediment.

The conversion of organic phosphorus to phosphate occurs with bacterial decomposition of the organic matter; thus, a decrease in organic and an increase in inorganic phosphorus with depth in the sediment should be found if these forms could be distinguished analytically. However, accumulation of phosphate in the interstitial water (as observed in the Santa Barbara and Catalina Basins) cannot be related directly to the release of phosphate from decomposition of organic matter, as was possible for nitrogen, because the phosphate concentration is controlled by solubility equilibria. If the interstitial water is in equilibrium with the various solid-phase phosphates, release of phosphate from organic matter must result in precipitation of an approximately equivalent amount and would cause little change in the concentration in the interstitial water. However, concomitant with the bacterial decomposition of the organic matter are changes in the physical-chemical conditions in the sediment which alter not only phosphate solubility but also adsorption-desorption equilibria (CARRITT and GOODGAL, 1954).

It is evident that precipitation (or adsorption) of phosphate has occurred in the Santa Monica Basin sediment, since its concentration in the interstitial water of several layers is less than that of the overlying water. The very high soluble nitrogen to phosphorus ratio of the interstitial water supports this conclusion. The sediment of the Santa Monica Basin differs from the other sediments in its low *pH* and low content of organic matter and both of these factors may contribute to phosphate precipitation. Whether calcium precipitates as the carbonate or as the phosphate depends on the *pH* which controls the carbonate ion concentration. KRUMBEIN and GARRELS (1952) put the *pH* boundary at which pure calcium phosphate could form from sea water at about 7.5, which is near the *pH* existing in the Santa Monica Basin sediment. If calcium precipitation occurs in the other basin sediments the product would be calcite with a very low content of phosphate.

The organic matter as such may have a specific effect on the phosphate solubility. Calcium phosphate solubility is increased by humic acids in soils (CLARKE, 1924, p. 523). The presence of organic compounds which form chelation complexes with ferric and aluminium ions have a pronounced effect in decreasing the extent of phosphate precipitation by these ions (BRADLEY and SIELING, 1953, and references cited therein). Many of the effective organic compounds exist in soils as a result of the microbiological decomposition of plant and animal remains and therefore are presumably present in sediments as well.

The distribution of phosphate in the interstitial waters of the Santa Barbara and Catalina Basins also suggests that the *Eh* plays a major role in the solubility equilibria. In the former sediment, which is strongly reducing throughout, phosphate concentration increases rapidly from the surface downward, in the latter, phosphate increases

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markedly only in the zone of negative Eh which starts about 80 cm below the surface of the core. KLENOVA and BUDIANSKAYA (1940) also show a relation between phosphate concentration and Eh in sediments from the Arctic. Although KRUMBEIN and GARRELS (1952) believe that phosphate is independent of Eh in the marine environment, it is known that in fresh water sediments phosphate dissolves under anaerobic conditions and precipitates in aerobic environments (HUTCHINSON, 1952). The Eh effect most probably relates to its influence on the ferric to ferrous ratio which in turn controls the precipitation or solution of ferric phosphate.

It is apparent that bacterial processes influence the phosphorus cycle in two manners: (1) by conversion of organic phosphorus into inorganic during decomposition of organic matter, and (2) through control of environmental factors which determine phosphate solubility equilibria, such as pH, Eh, and the amount and kinds of residual organic matter. In the sediments investigated deposition took place in an environment of relatively low pH, low organic content, and an Eh near zero. Soluble phosphate accumulated in an environment of low Eh and relatively high pH and organic content. A sufficient concentration gradient exists in the latter environment to permit release of phosphate from the sediment into the overlying basin water. The magnitude of return cannot be calculated but must be less than for nitrogen since the concentration gradient is smaller.

SILICON

Basin water

The concentration of silicate increases from the water surface to the sill depths of the Catalina and Santa Barbara Basins at a more gradual rate and to a greater depth than either phosphate or nitrate. Below the sills of the Santa Barbara, Santa Monica, and Catalina Basins the silicate concentration is nearly uniform at average values of 125, 157, and 165 $\mu\text{g-a/L}$, respectively. These concentrations parallel the progressively greater sill depths. Thus, it is evident that silicate in the basins (like temperature, chlorinity, and oxygen) is at approximately the same concentration as that of the water which enters the basins at about sill depth.

Regeneration is suggested by the presence of the highest silicate concentration found in the basins, 172 $\mu\text{g-a/L}$, at a point 0.3 m above the bottom of Santa Barbara Basin. The bottom-most silicate measurements in the other two basins, 0.5 and 1.0 m above the bottom, were not appreciably greater than in water higher above the bottom and it is notable that in Santa Barbara Basin the second measurement above the bottom (0.8 m) was not greater in silicate than others higher up. Accordingly, the enrichment gradient of silicate in bottom waters is confined to a very thin layer as with the other nutrients.

Sediment

Interstitial water in sediment of the three basins presents a general but irregular increase of silicate content with depth. In only two basin cores are there analyses just below the sediment surface (Fig. 6) and in the more detailed of these, the core from Catalina Basin, silicate is nearly 800 $\mu\text{g-a/L}$. This concentration is four to five times that of the overlying basin water. Even greater concentrations of 1,400 to 2,300 $\mu\text{g-a/L}$ exist at mid-depths of between 45 and 145 cm in the cores, below which silicate decreases.

The general increase of silicate with depth is similar to that reported for sediments from other basins of the region by EMERY and RITTENBERG (1952). In the new cores, as in the earlier ones, there is a rough parallelism between silicate content and pH , though the scatter of points is such that it is evident that pH must be only one of the controlling factors. Possibly as important is the availability of organically derived amorphous silica, which is more soluble than inorganic forms such as feldspar and quartz of detrital sands. Dissolved silicate is lowest in the Santa Monica Basin

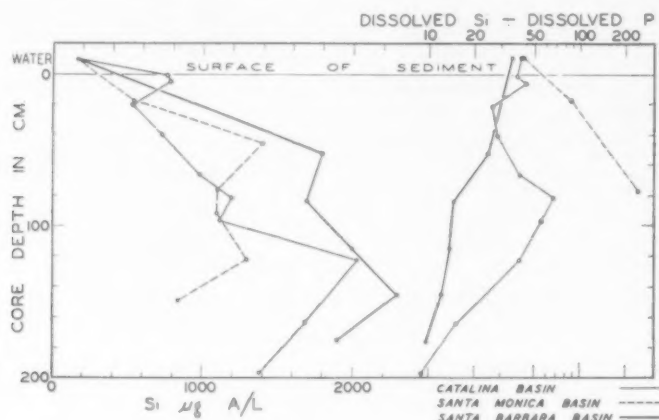


Fig. 6. Variation of silicate and dissolved silicon-phosphorus weight ratio with depth in basin sediments.

sediment, which contains a higher percentage of detrital sand grains and is of lower organic content than the sediment of the other basins; also the decreased silicate near the bottoms of the cores in both the Santa Monica and Catalina Basins occurs in somewhat coarser layers having more detrital sand grains than the sediment nearer the surface.

The weight ratio of dissolved silicon to phosphorus in the interstitial water decreases with depth in the core from Santa Barbara Basin, showing that phosphate is accumulated faster at depth than is silicate. In contrast, the few data from sediment of Santa Monica Basin show an increased ratio with depth, supporting the previous conclusion that phosphate is deposited at depth in sediment of that basin. The ratio curve for the core from Catalina Basin is intermediate in position (Fig. 6) but below 100 cm the ratio rapidly decreases in response to the sharp increase of dissolved phosphate.

SUMMARY AND CONCLUSIONS

A study was made of regeneration of nutrients in three basins selected on the basis of the oxidation-reduction potential of their sediments: Santa Barbara with negative Eh from top to bottom of cores, Catalina with positive Eh at top and negative at bottom of cores, and Santa Monica with an irregular variation from slightly positive to slightly negative Eh . As expected, nutrients in the interstitial water of these sediments exhibit wide ranges of variation, permitting an estimate of the effect of chemical environment upon regeneration from sediments.

In all three sediments organic nitrogen decreases with depth of burial and ammonia nitrogen increases, reaching concentrations of 3,000 times that in sea water. Nitrate and nitrite form from ammonia in the oxidizing sediment but not in the reducing sediment. The highest nitrate concentration, six times that of sea water, was near the surface of the Catalina Basin sediment. The inorganic nitrogen accumulating does not balance the organic nitrogen disappearing and, consequently, nitrogen is passing from the sediment to the overlying water. A consideration of the nitrogen cycle and the chemical data shows that only ammonia enters the water from reduced sediment, whereas ammonia, nitrite, nitrate, and molecular nitrogen can enter from sediments of the Catalina Basin type. The distribution of nitrogen components and their relationship to Eh strongly indicates that bacterial activity is dominant in regeneration of nitrogen.

Phosphate increases markedly with depth where Eh is negative and pH is high; maximum concentrations were about 50 times that of sea water. In contrast, where Eh is positive and pH low, phosphate shows little change with depth. At some depths its concentration is less than in sea water so that deposition from solution must have occurred. Conceivably, the nodular phosphatic Miocene shales of the Los Angeles Basin (HOOTS, 1930, pp. 105-106) may have been deposited in a similar environment. Unlike nitrogen, total phosphorus is nearly constant with depth, having values that are similar to inorganic stream-borne sediments. It cannot be decided from the data available whether the increased phosphate in the interstitial water is derived from organic or inorganic components or both. The standing concentration is determined by solubility equilibria that change with Eh, pH, and other environmental factors. Bacteria have a dual role in the phosphorus cycle: decomposition of organic phosphorus and modification of the physical-chemical environment.

Silicate in the interstitial water increases irregularly with depth to concentrations of about 10 times that of sea water. It is independent of Eh but may be related to pH, since greatest concentration exist in zones of highest pH. The correlation is, however, only approximate. It appears that regeneration of silicate is by solution of siliceous skeletal material, probably chiefly of diatoms, with bacterial modification of the environment a key factor.

Active regeneration of nutrients within the sediments, resulting in a marked concentration gradient between interstitial and overlying water, leads to enrichment of the latter by diffusion. Some nutrients may also be carried out of the sediment with water that escapes by mixing or channelling. For nitrogen, the quantity returned to the water is about 0.4 per cent of the annual use by phytoplankton in the region. Similar or smaller contributions probably occur for phosphorus and silicon. Enrichment of nutrients in the bottom water was observed, but only within 0.5 m of the bottom and, as predictable, it was not present for phosphate where phosphate was low in the sediment (positive Eh, low pH) nor for nitrate where nitrate was low in sediment (negative Eh). Correspondingly, oxygen exhibits a slight and somewhat uncertain decrease in concentration near the bottom. Restriction of the gradients of nutrients and oxygen to the bottom-most layer of basin water indicates that there must be relatively rapid mixing near the bottom. Mixing also is shown by bottom current measurements (REVELLE and SHEPARD, 1943).

BROUARDEL and FAGE (1954) and KOCZY (1950) found a much greater decrease of oxygen near the bottom in other areas. It is probably significant that these authors were dealing with oxygen contents of 4 to 8 ml/L rather than the low values of 0.2 and 0.4 which characterize the bottom waters of California basins. They attribute the decrease to oxygen withdrawal by the benthonic fauna which may be more abundant in the waters of higher oxygen content. KOCZY also found a decrease of phosphate and silicate in the bottom 40 m. Possibly, the decrease of phosphate may in part be the result of precipitation in the red clays and globigerina oozes, which are known to be of positive Eh.

Mixing of bottom water with overlying water of the basins should enrich the latter in nutrient nitrogen and silicate and deplete it in oxygen if no replacement from the open ocean occurs. Phosphate should be enriched or depleted depending on the type of sediment. The fact that the concentrations of nitrate, phosphate, silicate, and oxygen in the basin water are about the same (within the error of measurement) as those at sill depth indicates that replacement of basin water is very rapid in contrast to general opinion. It was shown that the release of ammonia from the sediment during only 20 years could produce an increase of $5 \mu\text{g-a/L}$ of nitrate in the entire 45 km^3 of water below the sill of Santa Barbara Basin if no replacement occurred. Since the waters below and above the sill contain identical nitrate concentrations (within the $5 \mu\text{g-a/L}$ error of measurement), the replacement must be complete in less than 20 years. Regeneration within the basin water would further reduce the estimated time required for replacement.

Rapid replacement of basin water is also indicated by computations based on oxygen used for oxidation of organic matter in the sediment. EMERY and RITTENBERG (1952) showed that about 3.0 ml/L of oxygen is required annually for oxidation in the top 30 cm of a 1 cm^2 column of sediment like that of Catalina Basin. Similar computations for the Santa Barbara Basin sediment of Table 3 showed about half as great an oxygen demand. Such a rapid use would exhaust all the oxygen present in the basin water in only about 2 years. Thus, consideration of both nitrate and oxygen relationships suggests that replacement of the water in basins off southern California requires only a few years.

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REFERENCES

- BRADLEY, D. B. and SIELING, D. H. (1953), Effect of organic anions and sugars on phosphate precipitation by iron and aluminium as influenced by pH. *Soil Science*, **76**, 175-179.
- BROUARDEL, J. and FAGE, L. (1954), Variation de la teneur en oxygène de l'eau au proche voisinage des sédiments. *Deep-Sea Res.*, **1**, 86-94.
- BRUJEWICZ, S. W. and VINOGRADOVA, E. G. (1946), Biogenic elements in the sediment solutions of the northern, middle and southern parts of the Caspian Sea. *C. R. Acad. Sci. URSS*, **54**, 419-422.
- CARRITT, D. E. and GOODGAL, S. (1954), Sorption reaction and some ecological implications. *Deep-Sea Res.*, **1**, 224-243.
- CLARKE, F. W. (1924), The data of geochemistry. *U.S. Geol. Survey, Bull.*, **770**, 841 pp.
- COOPER, L. H. N. (1937), The nitrogen cycle in the sea. *J. Marine Biol. Assoc.*, **22**, 183-204.
- DUSENBERRY, J. H. and POWELL, R. E. (1951), Reactions of nitrous acid. I. Ammonium nitrate decomposition. *J. Amer. Chem. Soc.*, **73**, 3266-3268.
- EMERY, K. O. (1952), Submarine photography with the benthograph. *Sci. Monthly*, **75**, 3-11.

- EMERY, K. O. (1954), Source of water in basins off southern California. *J. Marine Research*, **13**, 1-21.
- EMERY, K. O. and DIETZ, R. S. (1941), Gravity coring instrument and mechanics of sediment coring. *Bull. Geol. Soc. America*, **52**, 1685-1714.
- EMERY, K. O. and RITTENBERG, S. C. (1952), Early diagenesis of California basin sediments in relation to origin of oil. *Bull. Amer. Assoc. Petrol. Geologists*, **36**, 735-806.
- HARTMAN, OLGA (1955), Quantitative survey of the benthos of San Pedro Basin, Southern California; Preliminary results. *Allan Hancock Pacific Expeditions*, **19** (1), 185 pp.
- HOOTS, H. W. (1930), Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, California, *U.S. Geol. Survey Prof. Paper* 165-C, 79-134.
- HUTCHINSON, G. E. (1952), The biogeochemistry of phosphorus, In "*The Biology of Phosphorus*," edited by L. F. WOLTERINK, Michigan State College Press, East Lansing, Michigan, 1-35.
- JENSEN, H. L. (1953), Nitrification of pyruvic oxime by heterotrophic bacteria. *Proc. Intern. Bot. Congr. Stockholm*, 1950, **7**, 160-161.
- KLENOVA, M. V. and BUDIANSKAYA, M. L. (1940), Phosphorus in the sediments of polar seas. *C. R. Acad. Sci. URSS*, **28**, 82-86.
- KOCZY, F. F. (1950), Die bodennahen Wasserschichten der Tiefsee. *Naturwissenschaften*, **15**, 360-361.
- KRUMBEIN, W. C. and GARRELS, R. M. (1952), Origin and classification of chemical sediments in terms of pH and oxidation-reduction potentials. *J. Geol.*, **60**, 1-33.
- NEIDERL, J. B. and NEIDERL, V. (1942), *Micromethods of Quantitative Analysis*, 2nd ed., New York, John Wiley & Sons, 374 pp.
- POMEROY, R. and KIRSHMAN, H. D. (1945), Determination of dissolved oxygen, proposed modification of the Winkler method, *Ind. Eng. Chem., Anal. Ed.*, **17**, 715-716.
- REVELLE, R. and SHEPARD, F. P. (1943), Current measurements off the California coast in 1938 and 1939, *Records of Observations, Scripps Inst. of Oceanography*, **1**, 85-87, 150-159.
- RILEY, G. A. (1951), Oxygen, phosphate, and nitrate in the Atlantic Ocean, *Bull. Bingham Oceanog. Coll.*, **13**, 1-126.
- ROBINSON, R. J. and THOMPSON, T. G. (1948a), The determination of phosphates in sea water, *J. Marine Research*, **7**, 33-41.
- ROBINSON, R. J. and THOMPSON, T. G. (1948b), The determination of nitrites in sea water, *J. Marine Research*, **7**, 42-48.
- ROBINSON, R. J. and THOMPSON, T. G. (1948c), The determination of silicate in sea water, *J. Marine Research*, **7**, 49-55.
- SHERMAN, M. S. (1942), Colorimetric determination of phosphate in soils, *Ind. Eng. Chem. Anal. Ed.*, **14**, 182-185.
- SVERDRUP, H. U., JOHNSON, M. W. and FLEMING, R. H. (1942), *The Oceans*, New York, Prentice-Hall, 1087 pp.
- SZABO, Z. and BARTHA, L. (1951), Alkalimetric determination of nitrate by reduction with ferrous sulphate, *Magyar Kem. Folyoirat*, **57**, 84-86; *Chem. Abstracts*, **45**, 10133 (1951).
- THOMPSON, T. G., JOHNSON, W. R. and WIRTH, H. E. (1931), The sulphate-chlorinity ratio in ocean waters, *J. du Conseil Permanent International pour l'Exploration de la Mer*, **6**, 246-251.
- VARNER, J. E., BULEN, W. A., VANECKO, S. and BURRELL, R. C. (1953), Determination of ammonium, amide, nitrite, and nitrate nitrogen in plant extracts, *Anal. Chem.*, **20**, 1528-1529.
- WATTENBERG, H. (1937), Critical review of the methods used for determining nutrient salts and related constituents in sea water. *J. du Conseil Permanent International pour l'Exploration de la Mer*, **102**, 1-26.

On the fine-structure of the Gulf Stream front*

W. S. VON ARX, D. F. BUMPUS and W. S. RICHARDSON

DETAILED study of the water motion in the Gulf Stream has revealed a structure which, as far as one can tell, is best interpreted as a succession of short, overlapping segments which may be described as "shingles." Since shingling viewed from the gable end may have left- and right-hand symmetry with respect to the ridge pole, we may regard the shingle structure of the Gulf Stream as left-handed on the continental side looking down stream. FUGLISTER (1951), in his paper on the multiple currents of the Gulf Stream, was the first to suggest this possibility from consideration of temperature data alone. Since then the present authors (1953, 1954) have found evidence for both this and a similar but finer shingle structure through other kinds of observations from both ships and aircraft. MALKUS and JOHNSON (1954) followed one filament of the large-scale shingle elements in a drifting ship. The field observations to be described here indicate that several different scales of shingling occur simultaneously. Individual filaments have been traced which range in length from perhaps 500 to 100 km or less. Associated with these are smaller shingles some tens of km long or a complex multiple-front system extended a like distance. The existence of shingles less than 10 km long has been suggested by direct visual observation of the sea surface from aircraft.

It appears at the moment that the individual current filaments are distinguishable by their temperature, velocity, water type, and an associated slope of the isotherms below the surface, which is generally sharpest somewhere near the mid-length of the segment and blends into the background at each end. It is our experience that the overlap of these filaments is sufficient, in most cases, for the succeeding filament downstream to be intercepted from the air by flying 90° to the left of the heading steered when the evidence for the first streamer vanished into the background.

THE LONGITUDINAL PATTERN AS SEEN FROM THE AIR

During 26-27 February, 1953, an attempt was made to fly along the length of the Gulf Stream front between Miami, Florida and 70°W longitude. On this flight, as during an earlier flight made in November, 1952 (STOMMEL *et al.*, 1953), the Stommel-Parson airborne radiation thermometer was used together with photographic (VON ARX, 1953) and visual observations to determine the position of the frontal outcrop on the sea surface. The radiation thermometer consists of a Golay detector which, through optical means, alternately views the sea surface and a blackened body whose temperature is known. The signal from the detector is nulled by changing the temperature of the reference body so that its emission is equal to that arriving from the sea surface and the water vapour in the intervening atmosphere. The temperature of the reference body is regarded as representative of that of the sea surface. The

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course of the flight was determined partly by this temperature information, and partly by visible indications of the edge of the current, which include the contrast in water colour between Gulf Stream water and Slope water, the change in sea state across the frontal outcrop, the accumulated Sargassum and flotsam over the frontal convergence, and, in calm weather, characteristic patterns of slicks which tend to lie parallel with the front in Slope water. The aircraft was flown at an altitude of 1,500 ft. (under cloud base), and its position fixed by Loran at intervals of a few minutes when it was possible to follow the outcrop, and at crossings of the outcrop when a zigzag flight plan was employed. Fig. 1 shows the observed frontal outcrop.

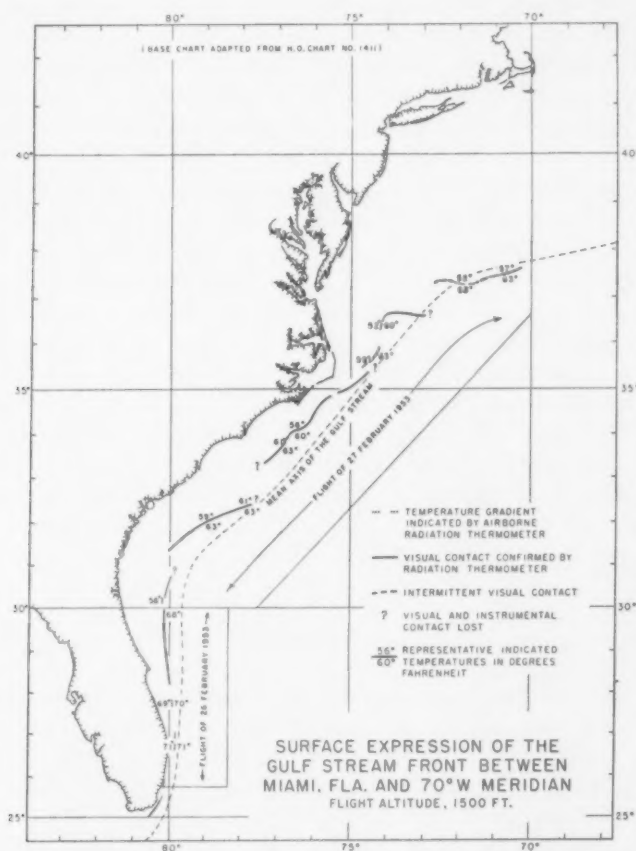


Fig. 1.

In following each segment, one had the experience that the temperature contrast across the front, and the change of sea state and sea colour coincident with the temperature contrast, grew stronger and then fainter as observations were pursued down stream, until at last none of these clues were sufficiently pronounced to direct the aeroplane further. The course was then changed 90° left (as earlier experience directed) and in every case contact with the frontal outcrop was re-established. This fresh contact was usually strong, so that one can infer that the filament extended

up stream some distance. Thus the pattern of filaments plotted in Fig. 1 does not show the overlap that was probably present. Visual observations from the aeroplane at this time indicated a fine shingle structure, usually left-handed, which interrupted the continuity of the frontal outcrop at intervals in the order of 10 km. When horizontal visibility was good, it was possible to fly across these individual irregularities without losing track of the larger scale features.

The relationship between the frontal position detected from ships and from aircraft has been studied to some extent. The aeroplane is capable of detecting only the superficial expressions of the frontal structure which, it is known, may differ in position from that of the steepest horizontal gradients of temperature at depths of 100 to 200 metres. STRACK (1953) has shown that the discrepancy between the greatest temperature contrast at the surface and at 100 metres may be as much as 50 miles or more in summer, but much more closely correlated in winter. Therefore the evidence given by the radiation thermometer is probably most reliable geographically during the winter months, when this flight was made.

On 5th and 6th June, 1953 it was possible to observe the position of the frontal outcrop from the air at the same time that a ship on the sea surface below made observations of the horizontal transverse temperature gradient to a depth of 200 metres. On 5th June the frontal outcrop was sharp as seen from the air, and its position was found to be 5 miles shoreward of the position of the greatest temperature contrast at a depth of 200 metres as shown in Section W. On the following day the aeroplane was unable to find a front in the vicinity of the ship and, indeed, a traverse shown in Section Y across the Gulf Stream revealed no sharp temperature contrast in the upper 200 metre layer. These two observations are not sufficient to establish the identity of aerial and shipboard observations of the frontal position in all instances, but they suggest a correlation which, in the presence of other evidence, seems worthy of provisional acceptance.

SERIAL SECTIONS FROM SHIPBOARD

The shingle structures of the Gulf Stream are probably migratory and possibly ephemeral. It has not been possible as yet to make consecutive aerial observations that would show either the direction or speed of migration of these features or their changes with time. However, a succession of crossings of the Gulf Stream axis made with the R/V *Caryn* (Cruise 64) in the area shown in Fig. 2 show that the velocity and the temperature contrast of the currents change rapidly with time, even in the course of a single day. In all, 26 sections (A through Z) were made at right angles to the mean axis of the Gulf Stream in the offing of Onslow Bay. When everything was in good order, it was possible to sail the ship across the current at least twice and sometimes three times during a 24 hour interval. Steering with the aid of the GEK it was possible to compensate for downstream set and thus to keep the plane of observation nearly fixed in space. Three groups of 5 and one group of 9 consecutive sections were made during the period 16 May through 7th June, 1953. Observations included measurements of surface salinity (Fig. 3a), temperature to a depth of 200 metres by means of the bathythermograph (Fig. 3b, c, d), and of the surface velocity (Fig. 3 and Sections A-Z) by means of both the GEK and the Loran dead-reckoning method. The values recorded on Sections A-Z were obtained by GEK. The mode

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of Loran DR velocities was greater by a factor 1.46, the interquartile range being 1.41 to 1.55.

The results show that the surface motion is directed alternately on shore and off shore in the course of two or three weeks. A similar regime of motion in the sub-surface water has been inferred by BUMPUS (1955) and BUMPUS and PIERCE (1955) from hydrographic and biological evidence obtained on the continental shelf in the

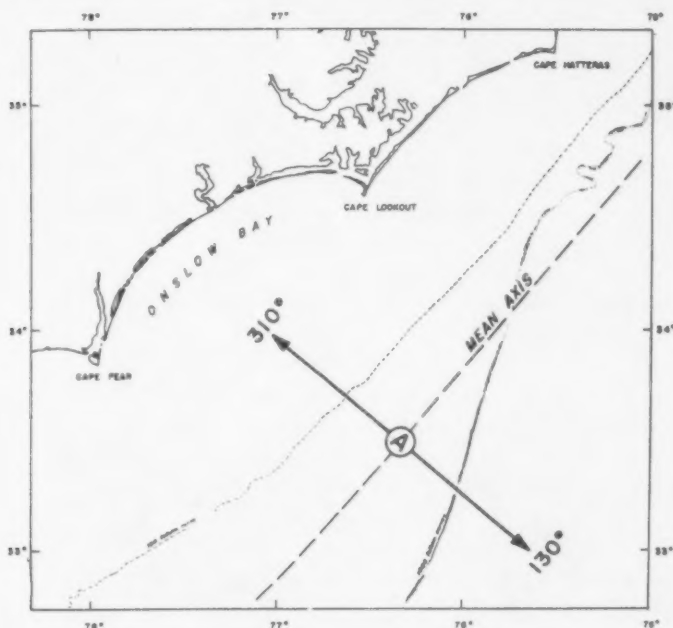


Fig. 2. Site of the serial sections made by R/V *Caryn*. The point A, marking the intersection of the line of traverse with the mean axis of the Gulf Stream, is indicated on Figs. 3a, b, c, d, and Sections A-Z.

offing of Onslow and Raleigh Bays. Corresponding migrations of the temperature field, but an imperfectly related strengthening and weakening of the horizontal temperature contrast, are also evident. The successive sections are designated A through Z. The group A through I revealed a strong tendency to offshore surface motion with increasing horizontal temperature contrast at 200 metres. The horizontal temperature contrast was also strong in the group J through N when the current was essentially parallel to the coast, and increasing contrast is to be noted in the group Q through U when the current direction changed from slightly offshore to onshore. A weakening of horizontal temperature contrast is to be noted in the group V through Z when the current direction was shifting from parallel to the coast to offshore. If anything, these observations suggest that the temperature contrast may increase when the surface current has a strong onshore or offshore component, but even this relationship is not without exception.

The characteristic maximum surface velocities observed by GEK and Loran DR fluctuated between 1.5 and 3 m/sec. The rate of change of surface velocity was notable. It was found that the persistence of velocity at any point on the section

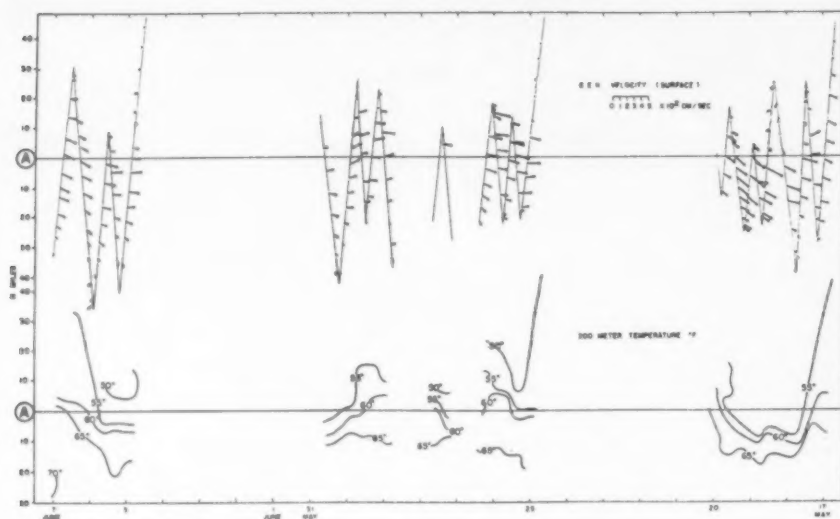


Fig. 3.

SALINITY IN ‰ AT SURFACE CARYN 64

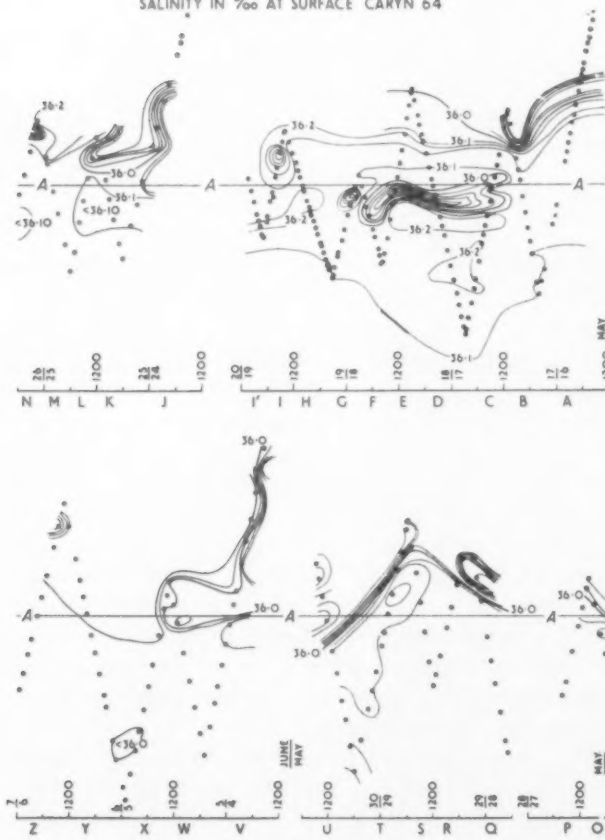


Fig. 3 (a).

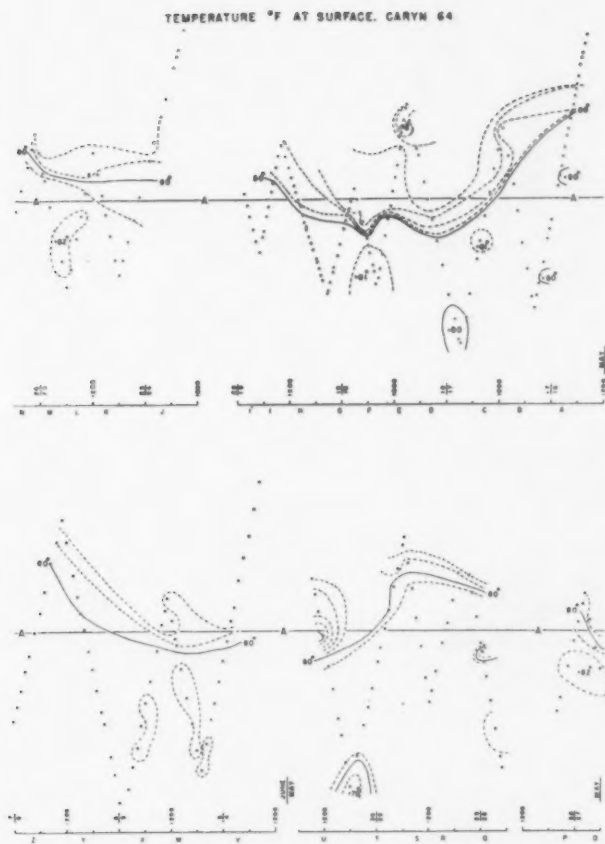


Fig. 3 (b).

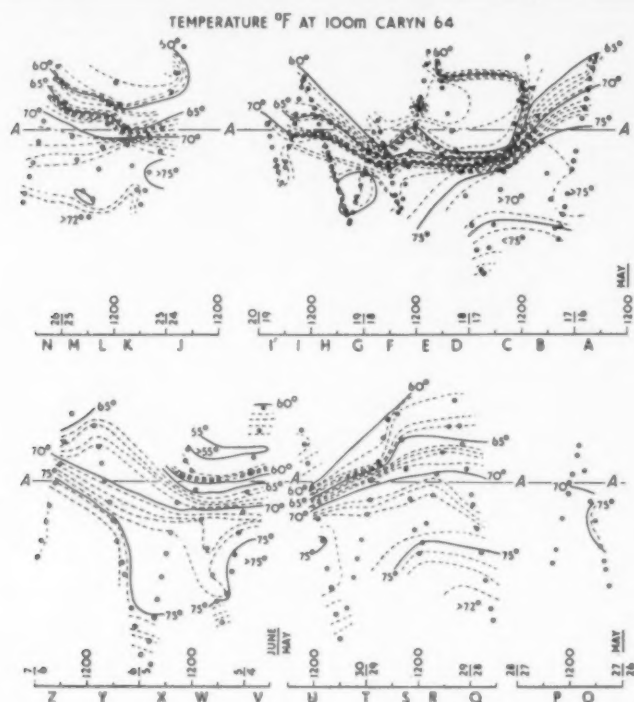


Fig. 3 (c).

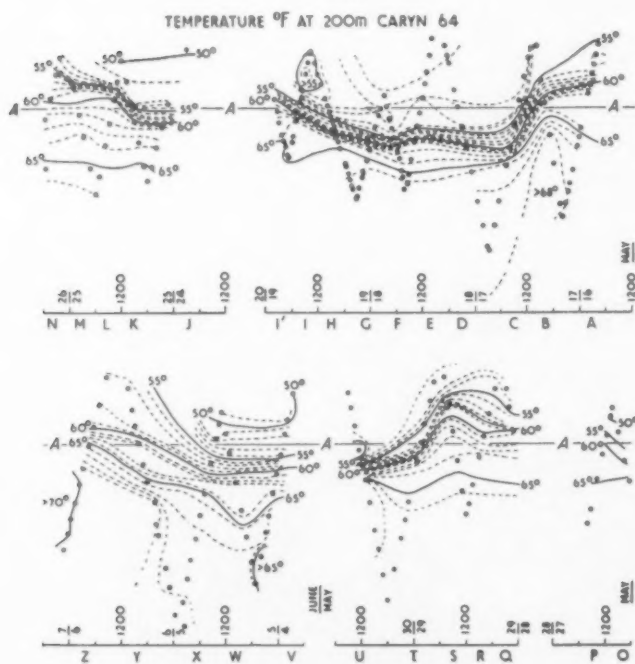
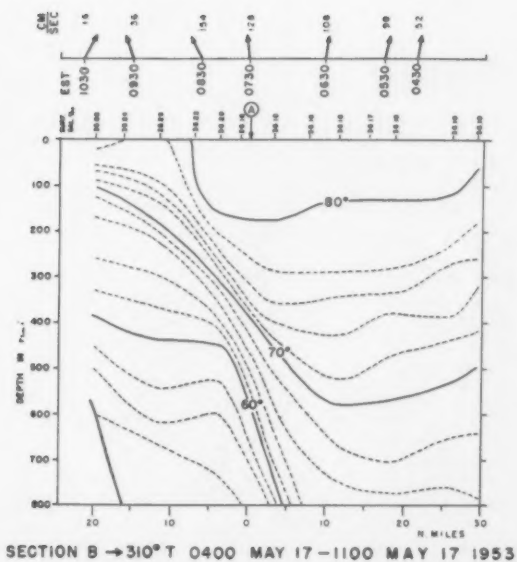
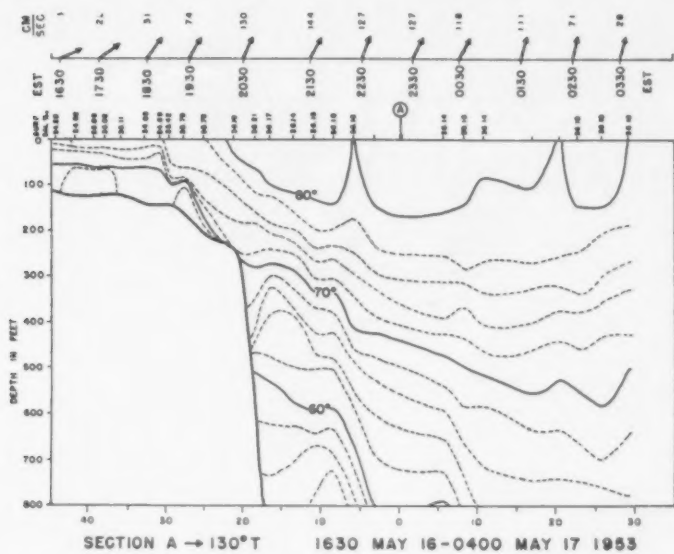
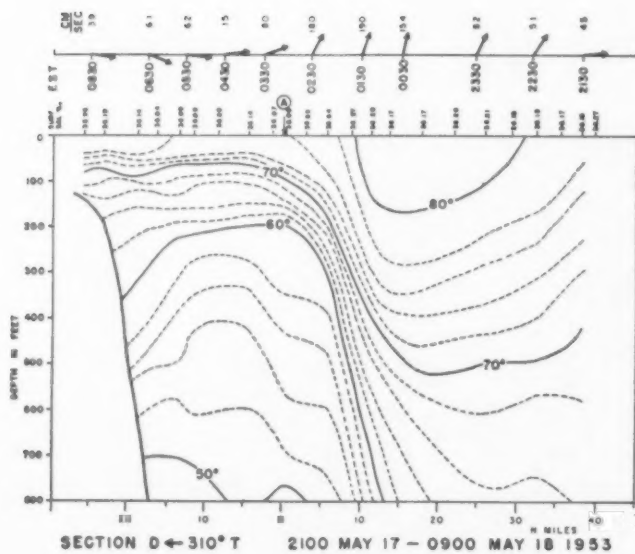
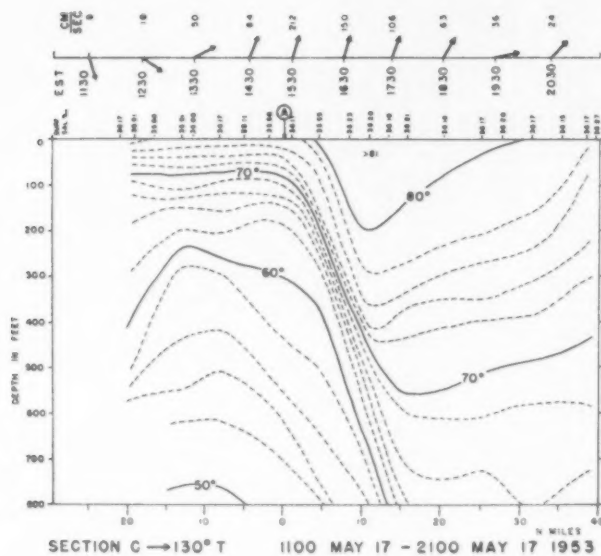
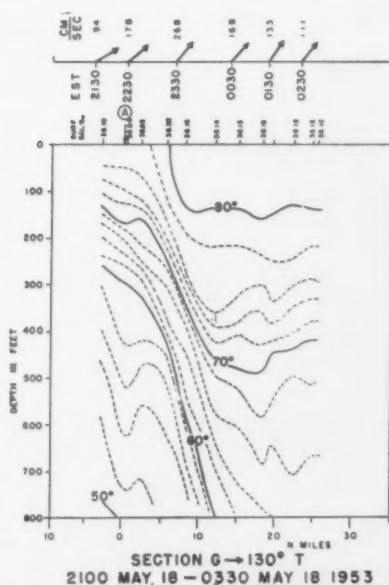
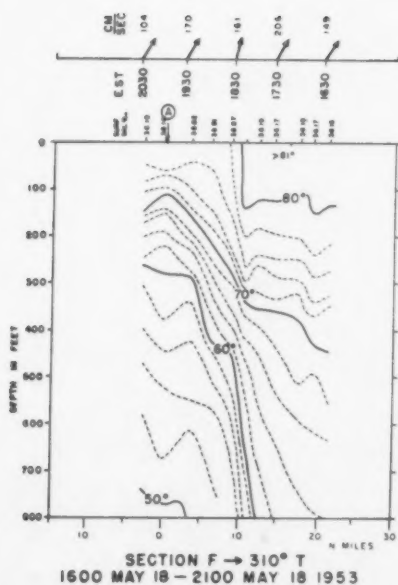
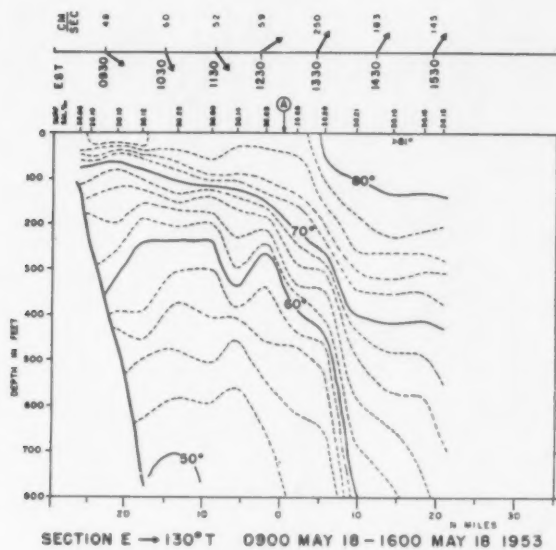
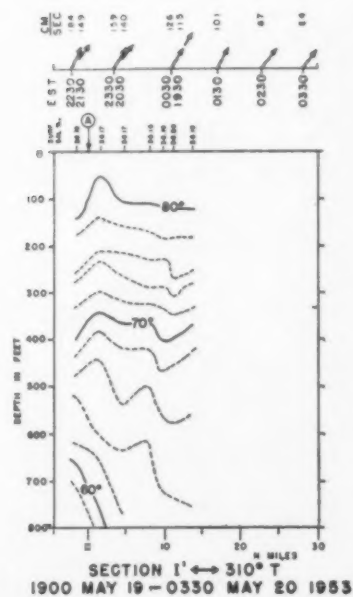
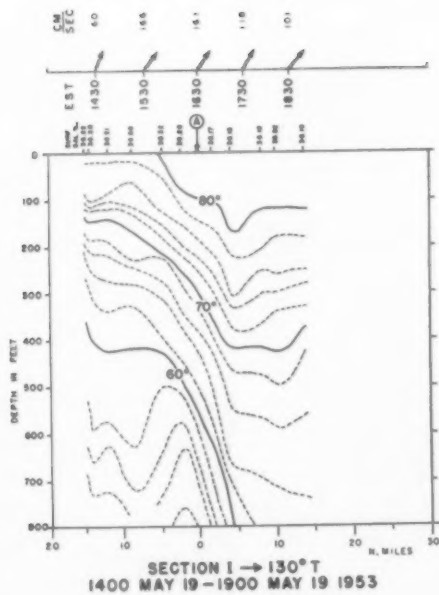
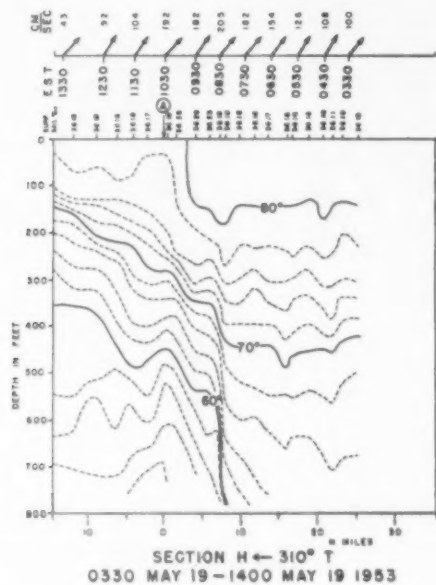


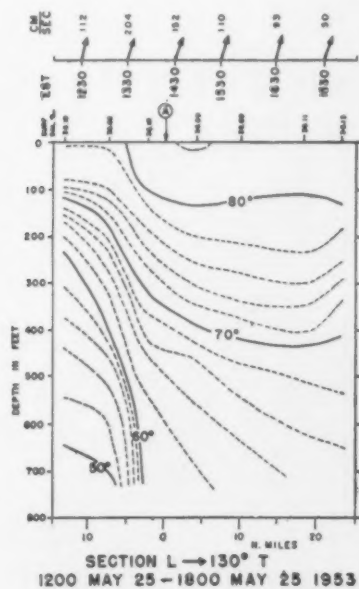
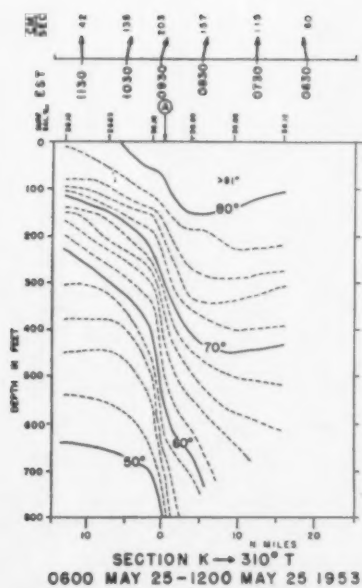
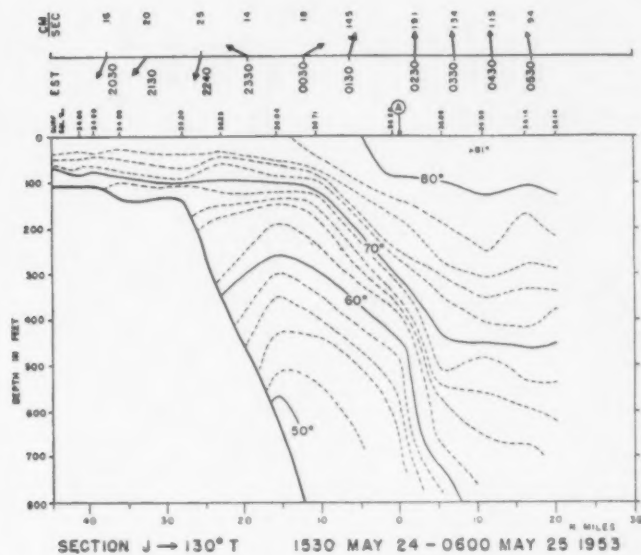
Fig. 3 (d).

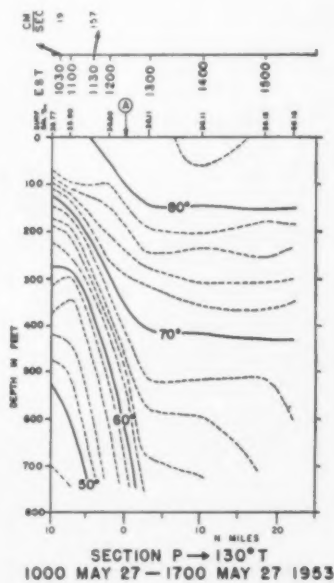
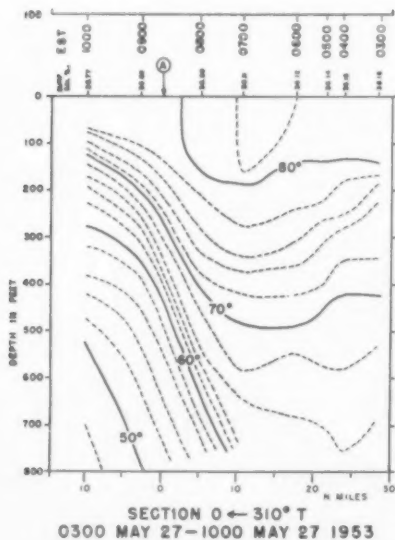
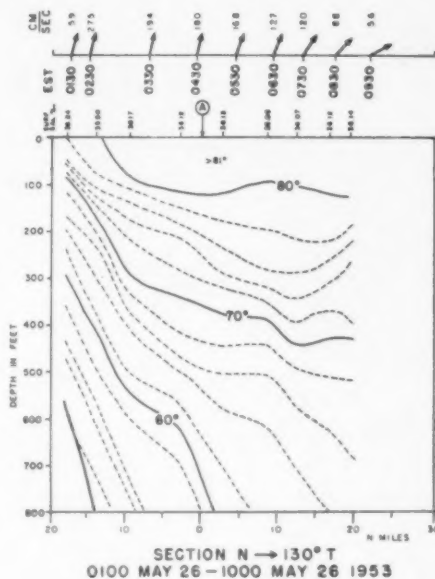
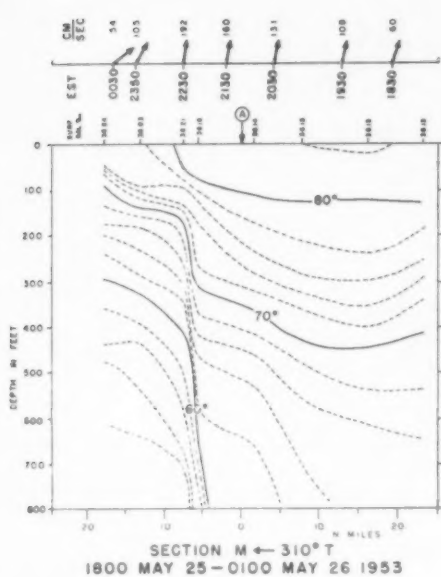


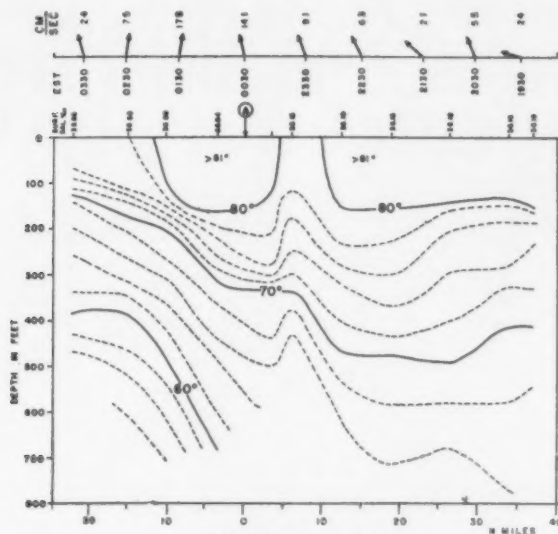




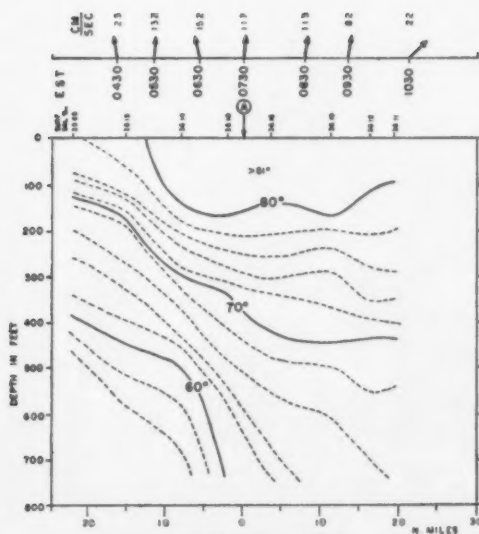




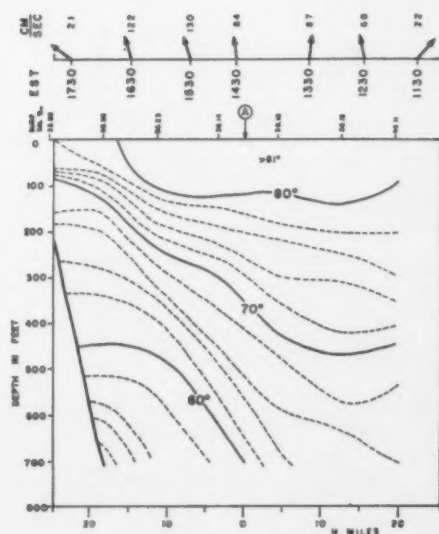




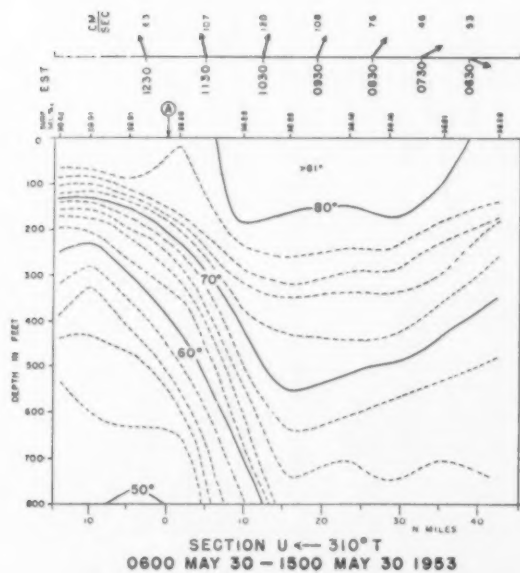
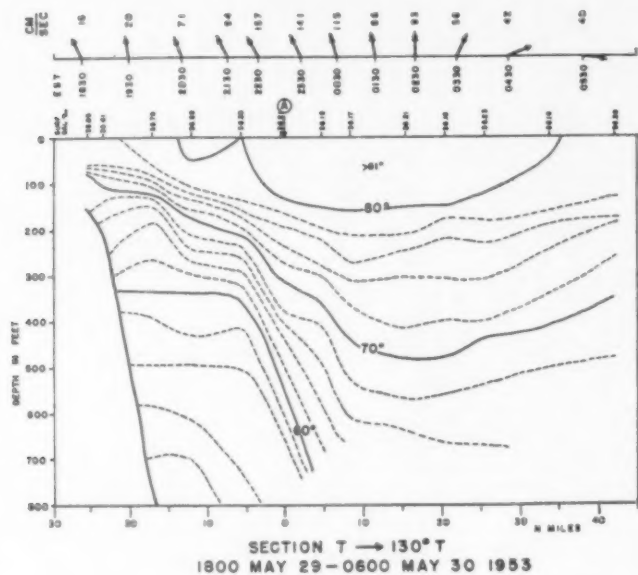
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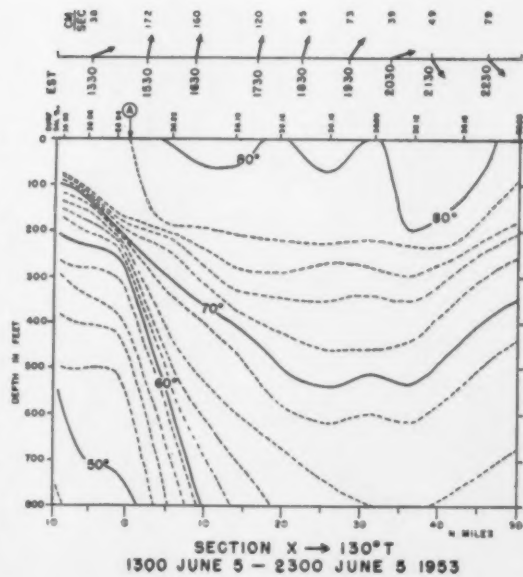
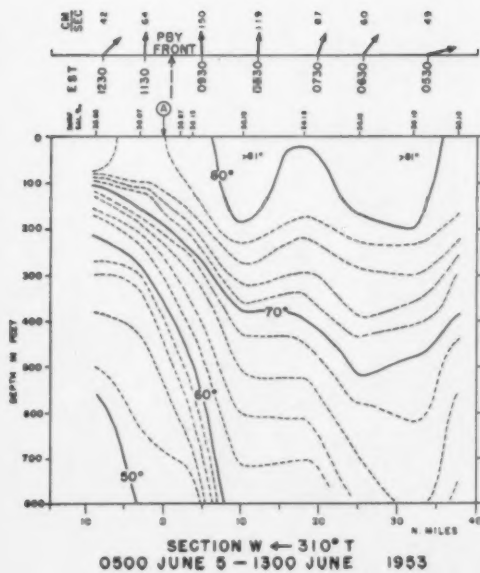
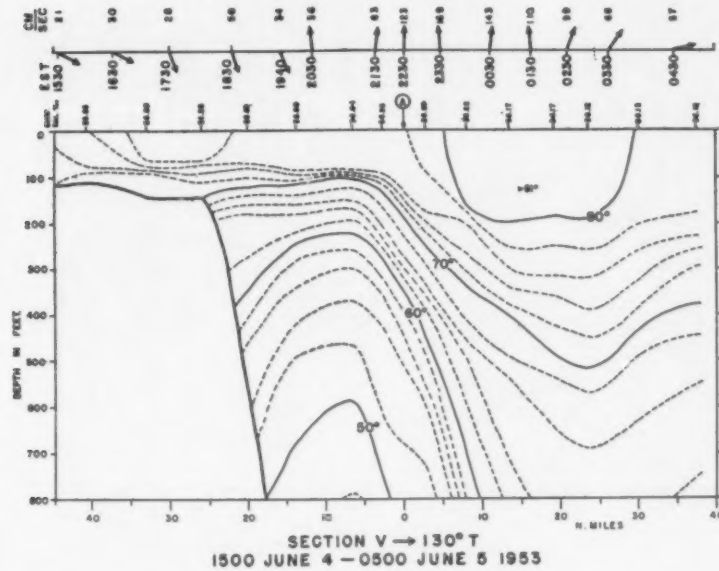


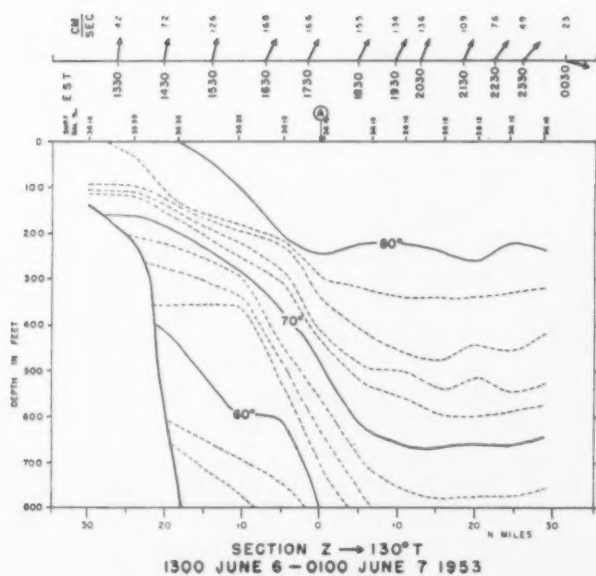
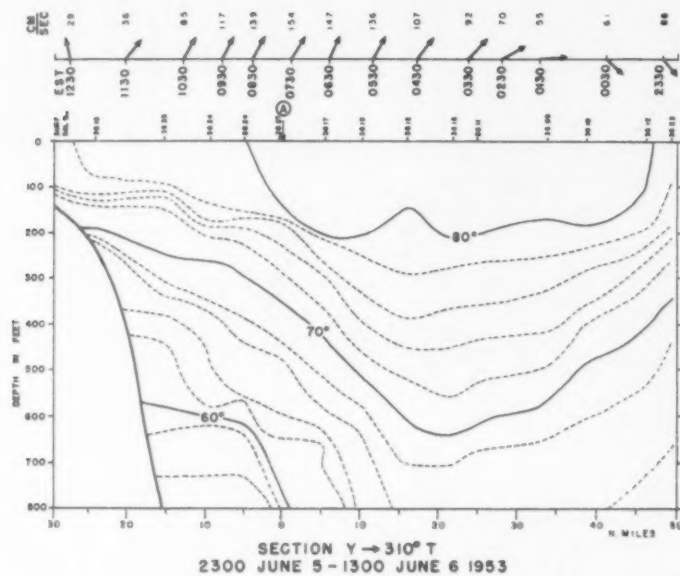
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was limited to 3 or 4 hours. The vectors shown in Fig. 3 were observed hourly, and one can see that in almost every case there was an appreciable change in current speed and direction within 2 hours of the turning point on successive sections. One can also see that within a matter of a day or two the character of surface motion could change from a diffluent to a confluent regime. The strongest currents appear to be associated with the strongest salinity contrasts, as might be expected, and it seems evident that, in addition to the normal gradient of salinity off the coastline, there are longitudinal irregularities associated with the current structure.

A POSSIBLE INTERPRETATION OF RESULTS

PILLSBURY (1880) was probably the first to detect fluctuations in the flow of the Gulf Stream by direct measurements in the Straits of Florida and in the offing of Cape Hatteras. PARR (1937) reported similar fluctuations of salinity and temperature in the Straits of Florida, which he related to changes in the surface velocity observed with a taffrail log. Recently WERTHEIM (1954a, 1954b) has obtained electro-magnetic measurements of the fluctuations of volume transport through the Straits of Florida which vary by a factor of about 2. MURRAY (1952) and WAGNER and CHEW (1953) have also reported short-period fluctuations in the surface current from GEK observations in the offing of Miami.

The filamentary structure of the Gulf Stream suggested by FUGLISTER in 1951 seems to be borne out in subsequent observations by MALKUS and JOHNSON and the present writers.

The characteristic velocities in the cores of Gulf Stream current filaments appear to be in the neighbourhood of $1\frac{1}{2}$ to 3 m/sec. During a 24 hour period a parcel of water moving within this range of speeds would cover a distance ranging from 130 to 260 km. This is roughly the range of length of the segments observed from the air, and the longest of them is not in disagreement with the lengths of the filaments plotted by FUGLISTER (1951, 1955), the interval between successive hot patches reported by FUGLISTER and WORTHINGTON (1951), and the length of drift obtained by MALKUS and JOHNSON (1954). In view of this evidence, it is conceivable that each filament in the structure of the Gulf Stream may be in some way related to a day's discharge of water from the Gulf of Mexico. This discharge in turn may be related to the tidal sequence in the Gulf of Mexico which, it is well known from the works of HARRIS (1897, 1900) ENDRÖS (1908), WEGEMANN (1908), STERNECK (1921), and SCHUREMAN (1940), is predominantly diurnal, being interrupted at fortnightly intervals by a short succession of weak semidiurnal tidal seiches. The diurnal tide in the Gulf of Mexico is essentially in phase at all points around its perimeter (GRACE, 1932), which requires that there be a diurnal change in the volume of water in the Gulf when this tidal species predominates. Since the flow through the Straits of Florida is uni-directional, the increase in volume required for rise in the diurnal tide must be accomplished through a change in the rate of outflow through the Straits of Florida if the rate of inflow through the Yucatan Channel is constant.

To speculate further on this assumption: the flow through the Yucatan Channel and the Straits of Florida is given by SVERDRUP (1942) as 26×10^6 m³/sec, by MONTGOMERY (1941) as between 26 to 30×10^6 m³/sec, and by PARR (1937) as between 30 and 34×10^6 m³/sec. The amplitude of the average diurnal tide in the Gulf of Mexico can be said to be .4 metres and, its area 1.3×10^{12} m². Hence the volume

that must enter to supply this rise in the diurnal tide is approximately $5 \times 10^{11} \text{ m}^3$. If the average rate of inflow through the Yucatan Channel is $30 \times 10^6 \text{ m}^3/\text{sec}$, the outflow through the Straits of Florida must be less than this figure in order for the tidal rise to occur. Assuming that the rate of rise is linear during a 12 hour period, approximately $10 \times 10^6 \text{ m}^3/\text{sec}$ must be contributed to effect the tidal rise, hence the flow through the Florida Straits must be this amount of short average, namely about $20 \times 10^6 \text{ m}^3/\text{sec}$ during the rise of diurnal tide; and on the ebb the Straits of Florida must transport about $40 \times 10^6 \text{ m}^3/\text{sec}$. Since the cross-sectional area of the Straits of Florida is not materially changed by the rise and fall of the diurnal tide, the mean velocity must change by something like a factor of 2 during the course of one diurnal tidal cycle. This requirement is not inconsistent with both the daily and weekly range of transport measured by WERTHEIM (1954a, 1954b). There are, however, other causes which may be invoked to explain the fluctuations of transport through the Straits of Florida, which will give the proper amplitude of variation at other than tidal frequencies due mainly to seasonal and synoptic changes in the wind field and pressure pattern of the atmosphere over the Gulf, Caribbean, and western North Atlantic areas.

At present there is no sound basis for relating the tidal sequence of any species to the short-period fluctuations of transport and velocity in the Gulf Stream. However, the coincidence of the range of variation of velocity and transport with the requirements of the tidal rise and fall is suggestive. The observations reported here offer evidence of fluctuations of considerable magnitude during the course of one day which, together with this and other evidence of longer period fluctuations, may be related to the shingle structure of the currents composing the Gulf Stream.

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Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

REFERENCES

- BUMPUS, D. F. (1955), The circulation over the continental shelf south of Cape Hatteras. *Trans. Amer. Geophys. Un.*, **36** (4) (in press).
BUMPUS, D. F. and PIERCE, E. L. (1955), The hydrography and the distribution of Chaetognaths over the continental shelf off North Carolina. *Pap. Mar. Biol. & Oceanogr., Suppl. Deep-Sea Res.* **3**: 92-109.
ENDRÖS, A. (1908), Vergleichende Zusammenstellung der Hauptseichesperioden der bis jetzt unterzuchten Seen mit Anwendung auf verwandte Probleme. *Petermanns Mitteil.*, **54**: 86-88.
FUGLISTER, F. C. (1951), Multiple currents in the Gulf Stream System. *Tellus*, **3** (4): 230-233.
FUGLISTER, F. C. (1955), Alternative analyses of current surveys. *Deep-Sea Res.*, **2**: 213-229.
FUGLISTER, F. C. and WORTHINGTON, L. V. (1951), Some results of a multiple ship survey of the Gulf Stream. *Tellus*, **3** (1): 1-14.

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- GRACE, S. F. (1932), The principal diurnal constituent of tidal motion in the Gulf of Mexico. *Mon. Not. R. Astron. Soc., Geophys. Suppl.*, **3** : 70-83.
- HARRIS, R. A. (1897), Manual of Tides, I, *USC & GS Rept.* 357.
- HARRIS, R. A. (1900), Manual of Tides, IV, A. *USC & GS Rept.* 661.
- MALKUS, W. V. R. and JOHNSON, K. (1954), A drift study of the Gulf Stream. *Woods Hole Oceanogr. Inst. Tech. Rept.*, Ref. No. 54-67 (unpublished manuscript).
- MONTGOMERY, R. B. (1941), Transport of the Florida Current off Havana. *J. Mar. Res.*, **4** : 198-220.
- MURRAY, Kenneth M. (1952), Short period fluctuations of the Florida Current from geomagnetic electrokinetograph observations. *Bull. Mar. Sci. Gulf and Carib.*, **2** (1) : 360-375.
- PARR, Albert E. (1937), Report on hydrographic observations at a series of anchor stations across the Straits of Florida. *Bull. Bingham Oceanogr. Coll.*, **6** (3) : 1-62.
- PILLSBURY, J. E. (1880), Current measurements in the Gulf of Mexico, Straits of Florida, and off Cape Hatteras. *Rept. Dir. U.S. Coast Survey*.
- SCHUREMAN, Paul (1940), Manual of Harmonic Analysis and Prediction of Tides. *USC & GS Spec. Pub.* 98.
- STERNECK, R. (1921), Die Gezeiten der Ozeane. *Sitz. Akad. Wis. Wein. IIa*, **130** : 363-371.
- STOMMEL, Henry, VON ARX, W. S., PARSON, D. and RICHARDSON, W. S. (1953), Rapid aerial survey of Gulf Stream with camera and radiation thermometer. *Science*, **117** (3049) : 639-640.
- STRACK, S. L. (1953), Surface temperature gradients as indicators of the position of the Gulf Stream. *Woods Hole Oceanogr. Inst. Tech. Rept.*, Ref. 53-53 (unpublished manuscript).
- SVERDRUP, H. U., *et al.* (1942), The Oceans, Prentice-Hall, Inc., New York : 1087 pp.
- VON ARX, W. S. (1953), Cartographic principles applied to wide-field photography. *Photogr. Engineering*, **4** (2) : 60-73.
- VON ARX, W. S., BUMPUS, D. F. and RICHARDSON, W. S. (1954), Short term fluctuations in the structure and transport of the Gulf Stream System. *Woods Hole Oceanogr. Inst. Tech. Rept.*, 54-76 (unpublished manuscript).
- VON ARX, W. S. and RICHARDSON, W. S. (1953), Aerial reconnaissance of the surface outcrop of the Gulf Stream front. *Woods Hole Oceanogr. Inst. Tech. Rept.*, Ref. 53-24 (unpublished manuscript).
- WAGNER, L. P. and CHEW, Frank (1953), Some results of the Florida Current survey. *Univ. of Miami Marine Lab. Tech. Rept.* 53.9, (unpublished manuscript).
- WEGEMANN, G. (1908), Über sekundäre Gezeitenwellen. *Ann. Hydrog., usw.* **36** : 532-541.
- WERTHEIM, Gunther K. (1954a), Studies of the electric potential between Key West, Florida and Havana, Cuba. *Trans. Amer. Geophys. Un.*, **35** (6) : 872-882.
- WERTHEIM, Gunther K. (1954b), Studies of the electric potential between Key West, Florida and Havana, Cuba. No. II. *Woods Hole Oceanogr. Inst. Tech. Rept.*, Ref. 54-68 (unpublished manuscript).

Occurrence of bacteria in pelagic sediments collected during the Mid-Pacific Expedition

RICHARD Y. MORITA and CLAUDE E. ZOBELL

Abstract—Bacterial populations ranging from hundreds to thousands per gram wet weight were demonstrated in pelagic sediments (red clay and globigerina ooze) taken during the Mid-Pacific Expedition. The abundance of viable bacteria in these sediments decreased with core depth. Although certainly most important as geochemical and biological agents in surface sediments at the mud-water interface, living bacteria were found at the bottom of the longest cores examined, nearly 8 metres, representing material believed to have been deposited more than a million years ago. A few explanations are offered to account for the presence of bacteria in this material of great antiquity.

INTRODUCTION

In 1950 the Mid-Pacific Expedition afforded an opportunity to investigate the occurrence and kinds of bacteria in red clay and globigerina ooze. It was a joint expedition of the Scripps Institution of Oceanography and the U.S. Naval Electronics Laboratory, primarily for exploring the ocean floor between California and the Marshall Islands (see Fig. 1). Bottom profiles along the track, as indicated by echograms, have been reported by DIETZ *et al.* (1954). Numerous cores were collected from water depths ranging from 1,700 to 6,000 metres.

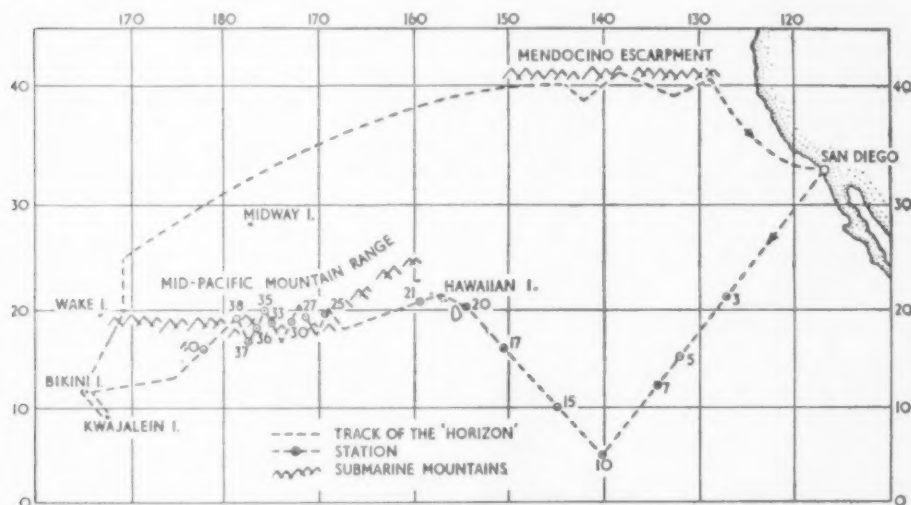


Fig. 1. Track of the Mid-Pacific Expedition. The R/V *Horizon* was accompanied by the EPC(R) 857 to Bikini Island.

Prior to 1950 little was known regarding life in pelagic sediments, although there is ample evidence for an abundant and physiologically versatile microflora in near-shore sediments collected from many different parts of the world (ZOBELL, 1946a). In the absence of field data some authors have tacitly assumed that, owing to inade-

quate organic nutrients, high hydrostatic pressures at great depths, and other adverse environmental conditions, pelagic sediments are mostly devoid of life. FISCHER (1894) noted the growth of only one or two bacterial colonies on plates of sea-water gelatin medium inoculated with one-gram samples of sediment taken from depths of 1523 and 2406 metres in the Gulf of Mexico, and he was not certain whether these were contaminants. WAKSMAN (1934) declared that true oceanic bottom deposits in the Atlantic contain few bacteria, but he gave no data to substantiate this conclusion.

In Pacific Ocean sediments of terrigenous origin, RITTENBERG (1940) found 10^4 to 10^6 bacteria per gram as compared with a maximum of 10^3 bacteria in the only pelagic sediment sample collected; this from a water depth of 3005 metres. That hydrostatic pressure is not a deterrent to bacterial life at great depths was demonstrated by ZOBELL (1952) and MORITA (1954), who found millions of viable bacteria per gram of sediments taken from depths exceeding 10,000 metres on the Danish *Galathea* Deep-Sea Expedition.

METHODS

Cores of bottom sediment were taken on the R/V *Horizon* with either a Phleger sampler or a modified Kullenberg piston-type corer. Immediately after being hoisted aboard the ship, the sediment was extruded and the core length measured. Strata representing different core depths were removed for bacterial analysis. Radially central portions of these core strata were dissected out with sterile instruments and transferred to wide-mouth bottles. In order to minimize the possibility of extraneous contamination, the freshly cut core strata ends were scraped clean two or three successive times with sterile instruments prior to taking the radially central sub-samples. These sub-samples were stored in the ship's refrigerator until they could be examined for the presence of bacteria; generally within an hour or two after the sample was taken.

The relative abundance of different kinds of bacteria in the sediment samples was estimated by the minimum dilution method. Several different kinds of nutrient media were employed, since no one medium can provide for the growth of all kinds of bacteria. Medium 2216E for the general aerobic population had the following composition:

Sea water	1000.0 ml
Bacto-peptone	5.0 gm
Ferric phosphate	0.1 gm
Yeast extract	1.0 gm

Medium 2216E fortified with KNO_3 (1.0 gm/L), soluble starch (2.0 gm/L) or gelatin (120 gm/L) was used to demonstrate the presence of nitrate-reducing bacteria, starch hydrolysers and gelatin liquefiers respectively. The general anaerobic bacterial population was estimated in medium 2216E treated with sodium formaldehydesulphoxylate (1.0 gm/L) to lower the redox potential, and resazurin (0.001 gm/L) to serve as an indicator of anaerobiosis. Sulphate-reducing bacteria were demonstrated in medium M 10 E:

Potassium phosphate dibasic	0.2 gm
Magnesium sulphate hydrated	0.2 gm
Sodium sulphite	0.1 gm
Ferrous ammonium sulphate	0.1 gm
Calcium lactate	3.5 gm
Ascorbic acid	0.1 gm
Bacto-peptone	1.0 gm
Yeast extract	1.0 gm
Bacto-agar	3.0 gm
Sea water	1000.0 ml

All media were adjusted to pH 7.5 and sterilized by heating in a pressure cooker to 121 °C for 30 minutes in $\frac{1}{2}$ oz. bottles fitted with plastic screw-caps. These receptacles can be manipulated

and stored on a ship at sea more conveniently than the more conventional cotton-wool stoppered test tubes commonly used by land-locked bacteriologists.

In each series the first bottle, containing 9.0 ml of sterile medium, was inoculated with 1.0 gram of wet sediment. It follows that if bacterial growth occurs in such bottles and not in uninoculated controls, there must be at least one viable cell per gram of sediment. The bacteria in the sediment were diluted to extinction by powers of 10 to estimate the order of magnitude of the bacterial population. The dilution procedure consisted of mixing, by vigorous shaking, 1.0 gm of sediment with 9.0 ml of medium and then transferring, with an automatic pipette, 1.0 ml of this 1 : 10 dilution to another 9.0 ml of sterile medium to give a 1 : 100 dilution. This operation was repeated serially until the sediment had been diluted 1 : 1,000,000. Assuming a random distribution of bacteria in the sediment, bacterial growth in the 1 : 10,000 and all lower dilutions but not in the 1 : 100,000 dilution, for example, would indicate the most probable number of bacteria in the sediment sample to be between 10,000 and 100,000 per gram or a bacterial titer of 4. The bacterial titer is defined as the logarithm of the reciprocal of the highest dilution showing growth or other evidence of physiological activity.

About 5 ml of air was left in the bottles of inoculated media prepared for aerobic bacteria. The bottles prepared for sulphate-reducing and other anaerobic bacteria were filled to capacity with sterile medium and the screw-caps were tightly sealed to exclude air.

The inoculated media were incubated for 21 days or longer, unless there was earlier evidence of bacterial activity. Increasing turbidity was generally indicative of bacterial growth. In questionable cases, particularly lower dilutions in which the sediment itself caused considerable turbidity, it was necessary to prepare wet mounts for examination by phase microscope in order to prove the presence of living bacteria. The media were tested for the appearance of nitrite or the disappearance of nitrate as indicative of the activity of nitrate-reducing bacteria :



Lugol's iodine was employed to test for starch, which is hydrolysed by certain bacteria. Gelatin liquefaction, indicative of the presence of active proteolytic bacteria, could be observed visually. The blackening of sulphate medium, caused by the formation of ferrous sulphide, was employed as a criterion of sulphate reduction :



Uninoculated bottles of media served as controls on sterility ; several bottles were maintained for many months without growth or other evidence of bacterial activity. Absence of growth or other activity in the higher (extinction) dilutions served as controls on technique.

FIELD OBSERVATIONS

Table 1 summarizes some of the properties of cores collected for bacterial analysis. The order of magnitude of the most probable number of bacteria per gram of wet sediment from the topmost and bottommost portions of the cores is given in terms of bacterial titer, which ranged from 0 to 4. Bacteria ranging in abundance from 10 to 10,000 per gram wet weight of sediment were demonstrated in all topmost portions of cores (*i.e.* material from the mud-water interface) and in nearly all deeper strata, regardless of water depth or core length. The pelagic sediments have far fewer bacteria than nearshore sediments of higher organic content. The latter commonly contain from 10^5 to 10^7 bacteria per gram wet weight.

The apparent preponderance of aerobic bacteria over anaerobic ones (see Tables 2 and 3) in sediment samples from most core depths was somewhat surprising, since there is ostensibly little or no free oxygen below the mud-water interface. Further observations are required to explain this anomaly. A good many of the bacteria have proved to be facultative aerobes, which grow preferentially in the presence of free

oxygen, but can grow slowly under anaerobic conditions when essential nutrients are present. It seems doubtful, however, that the apparent preponderance of aerobes is always ascribable to technical difficulties in demonstrating anaerobes.

Is it possible that free oxygen is generated *in situ*, by the electrolysis of water or alpha-particle bombardment from radioactivity, for example, at a rate sufficient to

Table 1. Bacterial titer of sediment at top and bottom of cores collected at different Mid-Pacific (MP) stations.

Station number	Location of Station		Water depth	Length of core	Type of sediment	Bacterial titer*	
	Latitude	Longitude				Top	Bottom
MP 3-1	N 20°51'	W 127°09·9'	m 4390	cm 747	Red clay	3	0
5-3	14°22·1'	133°06·8'	5300	40	Red clay	4	2
7-2	12°47·5'	134°26·4'	4758	106	Globigerina ooze	1	1
10-2	4°37·2'	140°00·3'	4365	89	Globigerina ooze	1	1
15-1	10°43·5'	145°53·2'	4987	92	Volcanic ash	4	2
17-2	14°38·3'	151°58·4'	5942	122	Red clay	3	3
20-2	20°27·0'	154°55·1'	3825	96	Red clay	4	2
21-2	20°47·0'	159°59·0'	4484	145	Red clay	4	4
25-E	19°02'	169°44'	1759	77	Globigerina ooze	4	4
27-2	19°35'	171°50'	3750	88	Globigerina ooze	3	3
30-1	18°27'	173°14'	3709	71	Red clay	2	2
33-H	17°53'	174°27'	1707	55	Globigerina ooze	2	1
33-L	17°51'	174°17'	1720	43	Globigerina ooze	4	1
35-1	19°21'	174°58'	4841	75	Red clay	4	4
35-2	19°02'	174°58'	3935	363	Red clay	3	3
36-1	16°48'	176°27'	5032	319	Globigerina ooze	4	3
37-1	17°06'	177°18'	5032	275	Globigerina ooze	4	2
38-1	19°02'	177°18'	4712	366	Red clay	3	0
40-1	15°35'	177°30'	4121	387	Red clay	3	0

- * 0 = No viable bacteria demonstrated in 1·0 gram of wet sediment.
 1 = At least 10 but < 100 viable bacteria per gram of wet sediment.
 2 = At least 100 but < 1,000 viable bacteria per gram of wet sediment.
 3 = At least 1,000 but < 10,000 viable bacteria per gram of wet sediment.
 4 = At least 10,000 but < 100,000 viable bacteria per gram of wet sediment.

provide for the oxygen requirements of aerobic bacteria? Active aerobes consume oxygen at a rate of 10^{-13} to 10^{-12} mg/cell/hour (ZOBELL, 1940). At this rate of oxygen consumption an aerobic bacterial population of 10^4 per gram of sediment would require only from about 10^{-5} to 10^{-4} mg of free oxygen per ml per year - the equivalent

of about 0.1 to 1.0 ppm per year. Possibly oxygen diffuses into bottom deposits rapidly enough to provide this much ; significantly the red clays and globigerina ooze samples are oxidizing in character.

Redox potential determinations on 236 samples from 19 cores of pelagic area sediments collected on the Mid-Pacific Expedition indicated that the red clay as well as the globigerina ooze at all core depths was in an oxidizing state. This is in direct

Table 2. Titer* of aerobic bacteria (first number in each column) followed by titer of anaerobic bacteria demonstrated in different strata of red clay cores collected at different Mid-Pacific Expedition stations.

Core strata (centimetres)	MP 3-1	MP 5-3	MP 17-2	MP 20-2	MP 21-2	MP 30-2	MP 35-1	MP 35-2	MP 38-1	MP 40-1
0 to 10	3, 2	1, 1	3, 2	4, 2	4, 2	2, 2	4, 3	3, 2	3, 3	3, 0
11 to 50		2, 0		4, 1			1, 2			
51 to 100			3, 3	3, 2	4, 2	2, 1	4, 2			
101 to 200			3, 3	2, 1	4, 0					
201 to 400								1, 1	2, 0	0, 0
400 to 750								3, 0	0, 0	0, 0

Table 3. Titer* of aerobic bacteria (first number in each column) followed by titer of anaerobic bacteria demonstrated in different strata of globigerina ooze cores collected at different Mid-Pacific Expedition stations.

Core strata (centimeters)	MP 7-2	MP 10-2	MP 25-1	MP 27-2	MP 33-H	MP 33-L	MP 36-1	MP 37-1
0 to 10	1, 0	1, 0	4, 1	3, 2	2, 1	1, 1	4, 4	3, 4
11 to 50			1, 1	2, 0		1, 4		
51 to 100	2, 2	1, 0	4, 2	3, 0	1, 1			
100 to 200	1, 0							2, 3
200 to 400							4, 4	1, 2

- * = No viable bacteria demonstrated in 1.0 gram of wet sediment.
 1 = At least 10 but < 100 viable bacteria per gram of wet sediment.
 2 = At least 100 but < 1,000 viable bacteria per gram of wet sediment.
 3 = At least 1,000 but < 10,000 viable bacteria per gram of wet sediment.
 4 = At least 10,000 but < 100,000 viable bacteria per gram of wet sediment.

contrast with nearshore sediments of high organic content in which reducing conditions (Eh = - 50 to - 350 mv) commonly prevail (ZOBELL, 1946b ; EMERY and RITTENBERG, 1952 ; MORITA, 1954).

Measurements made with a Beckman Model G meter, connected with bright platinum, glass and KCl-calomel electrodes inserted in the sediment samples, by the methods outlined by ZOBELL (1946b), showed Eh values ranging from + 150 to

+ 450 mv and pH values ranging from 6.58 to 7.97 in red clay. The redox potential of globigerina ooze ranged from + 150 to + 350 with pH values ranging from 7.47 to 7.55. There was little variation with core depth in either Eh or pH. The pelagic area sediments were fairly well buffered but very poorly poised, as indicated by the drift in Eh values while the determinations were being made. The poor poise, drift, or low O/R capacity is attributed to the low content of readily oxidizing or reducing constituents. Although the oxidizing capacity was low, the pelagic sediments were definitely oxidizing in character. This may help to account for the preponderance of aerobes over anaerobic bacteria.

An appreciable percentage of the bacteria were able to utilize the oxygen in nitrate as indicated by nitrate reduction. In general there were more proteolytic (gelatin-digesting) than saccharolytic (starch-hydrolysing) bacteria. Sulphate-reducing bacteria were sparse in numbers and sporadic in occurrence. These are the only strict anaerobes demonstrated in the pelagic sediments.

Morphologically the bacterial flora in the pelagic sediments closely resembled those in sea water and terrestrial sediments. Rod-shaped forms were by far the most prevalent with lesser numbers of vibrio, spirilla, and cocci. It is estimated that more than 90 per cent of the bacteria were short gram-negative rods ranging in length from 2 to 5 microns. Quite frequently elongated filamentous forms were observed in wet mounts. Very few spore-formers were detected. Yeasts were not observed, but mould fungi were fairly common, particularly in the topmost layers of pelagic sediment. Rather than being aerial contaminants, the moulds are believed to arise from spores that have settled to the sea floor.

DISCUSSION

The general occurrence of bacteria in all samples of recent pelagic sediments is noteworthy, this being the first evidence of an indigenous microflora in red clays and globigerina oozes. Finding no bacteria in some of the older material (MP3-1, core depth 747 cm; MP38-1, core depth 386 cm, and MP40-1, core depth 387 cm) is equally significant, because in the first place negative results speak favourably for aseptic sampling technique, and secondly indicate that we have reached the lower limits of the biosphere.

Incidentally, we are convinced, from years of experience and numerous checks and controls on sampling and analytical technique, that the possibilities of contamination are negligible. The principal error is in the other direction, namely getting results that are too low rather than too high. This is because no one nutrient medium or combination of cultural conditions required for a highly diverse microflora can provide optimal conditions for the growth of all species or strains of bacteria. The direct microscopic examination of recently collected material constitutes further evidence that bacteria are present in pelagic sediments, but unfortunately this technique offers no clues concerning the viability of the cells.

Unquestionably bacteria are present at a minimum abundance reported in Table 1, 2, and 3, and they are viable as indicated by their growth in nutrient media. Less certain is the actual state and geochemical importance of bacteria in the pelagic sediments. Those in recent sediments in the vicinity of the mud-water interface are believed to be playing an important part in the mineralization of organic matter, in consuming free oxygen, in providing particulate matter (bacterial cell substance)

as food for the associated bottom fauna, etc. ; but to what depth and in what age of sediments do these bacterial activities continue ?

According to ARRHENIUS (1952), red clays are deposited in the Pacific Ocean at an average rate of 2.3 mm per 1,000 years. At this rate some of the lower strata in cores MP3-1 and MP35-2, in which a minimum of 10^3 bacteria per gram were found, were deposited more than a million years ago. Have bacteria been acting on the material in these deposits for more than a million years, or are the bacteria in a state of suspended animation ? All available evidence points to a slow continuous activity of the bacteria.

Bacteria are more abundant, and there are more varieties, in the topmost layers of recently deposited sediment than in older sediments at greater depths. There is also a gradual decrease with depth (age) in the organic carbon content of pelagic sediments. Although the organic content of pelagic sediment is only 1 per cent. or less (REVELLE, 1944), the low concentration would not preclude the possibility of bacterial activity. Marine bacteria continue to be active in very dilute nutrient solutions, as has been pointed out by WAKSMAN and CAREY (1935) and by ZOBELL and GRANT (1943). The latter demonstrated bacterial multiplication and respiration after the organic content was reduced to 0.1 mg per litre (0.0001 per cent.).

Prolonging the period that bacteria could persist on low concentrations of organic matter is their ability to recycle carbon compounds until completely oxidized to carbon dioxide. Heterotrophic bacteria generally convert from 30 to 40 per cent. of the carbon of organic compounds into bacterial cell substance, the remainder being oxidized as a source of energy to carbon dioxide. Upon the death of the bacteria their protoplasm may provide carbon and energy for the growth of other bacteria.

Organic synthesis by autotrophic bacteria is another mechanism that may contribute to bacterial life in older sediments. Most of the sulphate-reducing bacteria found in marine sediments can utilize molecular hydrogen as a sole source of energy for the synthesis of protoplasm from the reduction of carbon dioxide or bicarbonate (SISLER and ZOBELL, 1954). If one could postulate or prove (e.g., through electrolysis, radioactivity, reaction of water on iron, etc.) the production of the essential hydrogen, autotrophic bacteria might merit much more attention by those who are concerned with a study of the lower limits of the biosphere or with the importance of bacteria as geochemical agents.

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REFERENCES

- ARRHENIUS, G. (1952), Sediment cores from the East Pacific. Pt. 1. Properties of the sediment and their distribution. Reports on the Swedish Deep-Sea Expedition, 5, 91 pp.
- DIETZ, R. S., MENARD, H. W. and HAMILTON, E. L. (1954), Echograms of the Mid-Pacific Expedition. *Deep-Sea Res.*, 1, 258-272.
- EMERY, K. O. and RITTENBERG, S. C. (1952), Early diagenesis of California basin sediments in relation to origin of oil. *Bull. Amer. Assoc. Petrol. Geol.*, 36, 735-806.
- FISCHER, B. (1894), Die Bakterien des Meeres nach den Untersuchungen de Plankton-Expedition unter gleichzeitiger Berücksichtigung einiger alterer und neuerer Untersuchungen. *Ergeb. Plankton-Exped.*, 4, 1-83.
- MORITA, R. Y. (1954), Occurrence and significance of bacteria in marine sediments. Dissertation, Univ. Calif., Los Angeles, 80 pp.
- REVELLE, R. R. (1944), Marine bottom samples collected in the Pacific Ocean by the *Carnegie* on her seventh cruise. *Carnegie Inst. Wash., Pub.* 556, (1), 180 pp.
- RITTENBERG, S. C. (1940), Bacteriological analysis of some long cores of marine sediments. *J. Mar. Res.*, 3, 191-201.
- SISLER, F. D. and ZOBELL, C. E. (1950), Hydrogen-utilizing sulfate-reducing bacteria in marine sediments. *J. Bact.*, 50, 749-757.
- WAKSMAN, S. A. (1934), The distribution and conditions of existence of bacteria in the sea. *Ecol. Monograph*, 4, 523-529.
- WAKSMAN, S. A. and CAREY, C. (1935), Decomposition of organic matter in sea water by bacteria. II. Influence of addition of organic substances upon bacterial activities. *J. Bact.*, 29, 545-561.
- ZOBELL, C. E. (1940), The effect of oxygen tension on the rate of oxidation of organic matter in sea water by bacteria. *J. Mar. Res.*, 3, 211-223.
- ZOBELL, C. E. (1946a), *Marine Microbiology*, Chronica Botanica Co., Waltham, Mass., 240 pp.
- ZOBELL, C. E. (1946b), Studies on the redox potential of marine sediments. *Bull. Amer. Assoc. Petrol. Geol.*, 30, 477-513.
- ZOBELL, C. E. (1947), Microbial transformation of molecular hydrogen in marine sediments with particular reference to petroleum. *Bull. Amer. Assoc. Petrol. Geol.*, 31, 1709-1751.
- ZOBELL, C. E. and CONN, J. E. (1940), Studies on the thermal sensitivity of marine bacteria. *J. Bact.*, 30, 223-238.
- ZOBELL, C. E. and GRANT, C. W. (1943), Bacterial utilization of low concentrations of organic matter. *J. Bact.*, 45, 555-564.

A neutral-buoyancy float for measuring deep currents

J. C. SWALLOW

Abstract—Floats designed to stabilize themselves at a given depth, and fitted with means of sending out acoustic signals to indicate their position, have been made at the National Institute of Oceanography. Some current measurements were made with them on a recent cruise of R.R.S. "Discovery II".

INTRODUCTION

A body which is less compressible than sea water will gain buoyancy as it sinks ; if its excess weight at the surface is small, it may at some depth gain enough to become neutrally buoyant, when no further sinking will occur. Following the movement of such a float would give a direct measurement of the current at that depth, free from the uncertainties involved in using a conventional current-meter from an anchored ship. The possibility of using this method for measuring deep drift currents over a long period has been suggested in a recent note by STOMMEL (1955).

THE FLOAT AND ITS SIGNALLING EQUIPMENT

In the present design, tracking the floats is made possible by fitting them with acoustic transmitters, capable of sending out a short pulse every few seconds for two or three days. Besides having a sufficiently low compressibility, the float must provide enough spare buoyancy to carry this transmitter, and must not collapse at the greatest working depth.

Aluminium alloy scaffold tubing (alloy specification HE-10-WP, described in B.S. 1476 (1949)) has the required mechanical properties, and can be made into convenient containers for the electrical circuits and batteries. The compressibility of a long tube, closed at its ends, is (see, for example, NEWMAN and SEARLE, 1948)

$$-\frac{1}{v} \frac{dv}{dp} = \frac{R_1^2/\mu + R_2^2/k}{R_2^2 - R_1^2}$$

where R_1 and R_2 are the internal and external radii, v is the external volume, and μ and k are the rigidity and bulk moduli of the tube material. In Fig. 1 this compressibility is plotted against the ratio wall thickness : mean radius. The buoyancy and collapsing depth are also shown, the latter being calculated from formulae given in B.S. 1500 (1949). It can be seen that, by reducing the thickness-to-radius ratio of the standard tube to 0.16, the buoyancy can be doubled without seriously impairing the low compressibility or restricting the working depth. The outside diameter of the tubes was reduced uniformly, by solution in caustic soda, to make the ratio 0.16 (± 0.01), and in this condition 6 m of tubing is needed for each float. For convenience in handling, this is made in two lengths of 3 m, one containing the transmitter circuit and batteries, and the other providing buoyancy.

Fig. 2 is a sketch of the float, with the end plugs shown in detail. The ends of the tubes are bored out to fit individual plugs ; this method of sealing scaffold tube has been tested to 4,500 m depth. The transmitter consists of a nickel scroll resonant at 10 kc/s, wound toroidally and energized by discharging a capacitor through a

flash tube. Originally the transmitter was arranged so that, besides sending out a steady series of pulses, it would respond when it received a signal from the ship's echo-sounder. Since no current measurements were made with this arrangement, however, only the simple circuit is shown here.

The mean density of each complete float and transmitter is adjusted to an accurately known value by immersing it in a salt solution of known density and temperature

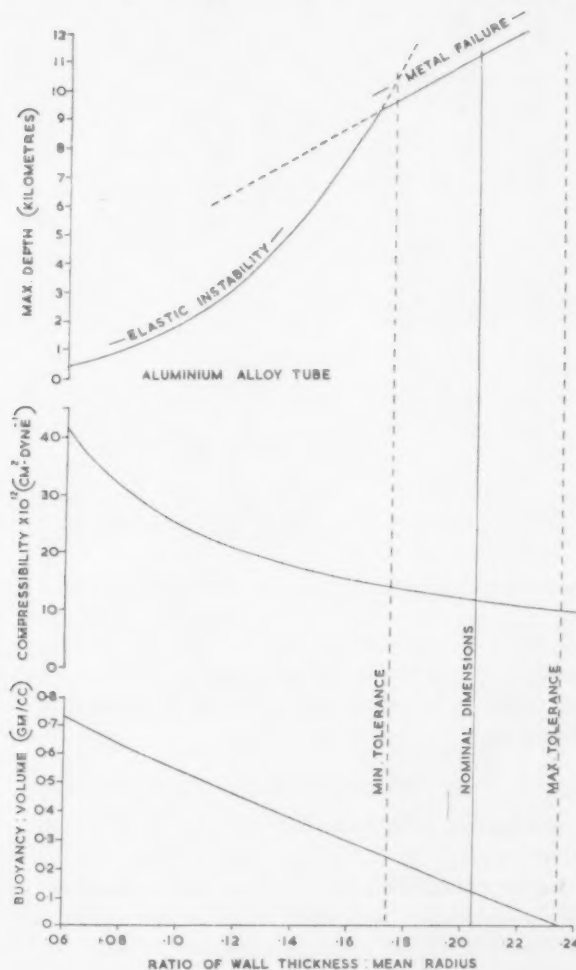


Fig. 1. Compressibility, buoyancy per unit volume, and maximum depth for aluminium alloy tubes.

(in the present case this was 1.0264 at 14.1°C) and adding weights until it is neutrally buoyant. This adjustment can be made to 1 gm. without difficulty, with a float weighing about 10 kg. in air. The density can be altered to any desired value by adding or subtracting weights, in proportion to the total weight of the float. All the extra weights are put inside the buoyancy tube, so that no change in volume has to be allowed for. Before launching any of the floats, temperature and salinity observa-

tions are made and the water densities *in situ* calculated from tables (ZUBOV and CZIHIRIN, 1940). The extra weight required to take the float down to any desired depth can then be determined, from the known density at that depth and the calculated compressibility of the float. Allowance has to be made for the tempera-

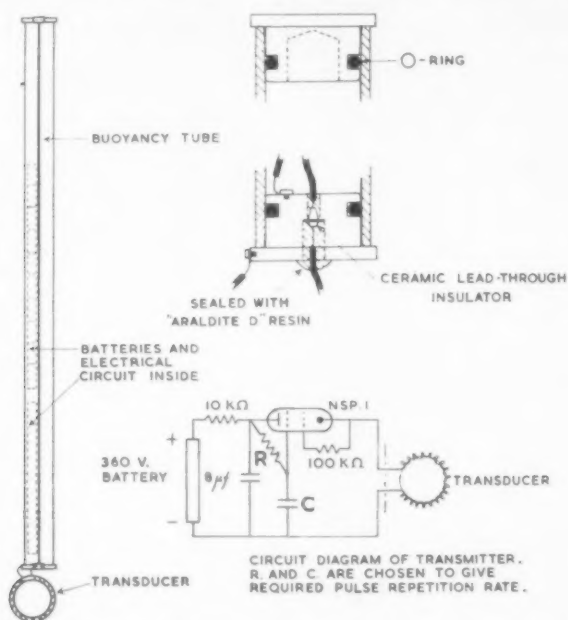


Fig. 2. Sketch of float and end plugs, and circuit diagram of acoustic transmitter.

ture change, but the effect of this is small. For an example of the order of magnitude of these extra weights, in the area where the present measurements were made, a float arranged to stabilize itself at 1,000 m depth had 38 gms. negative buoyancy at the surface.

METHOD OF TRACKING A DRIFTING FLOAT

The original plan was to follow the floats by means of the ship's echo-sounder, observing the responses of the floating transmitter when it was triggered by an outgoing echo-sounder pulse. This would have the advantage of indicating directly the depth of the float, but the narrowness of the beam of the echo-sounder made searching for the float very difficult and an alternative method had to be used. This scheme is illustrated in Fig. 3.

With the ship stopped head-to-wind, two hydrophones are lowered over the side, as far apart as can be conveniently arranged. The signals from them are fed via separate tuned amplifiers to a double-beam oscilloscope, the time-base of which can be triggered from signals applied to either beam. Pulses from the floating transmitter are received at different times at the two hydrophones, and the magnitude and sign of this time-difference can be measured on the oscilloscope.

As the ship's head falls away from the wind direction, the time-difference is observed as a function of the bearing of the line joining the hydrophones. It follows

a "figure-eight" polar diagram, with sharp zero-values when the bearing is at right angles to the line from the ship's position to the float. Usually, observations over an arc of about 120° are enough to indicate the bearing from the ship to the float. The process is repeated with the ship in other positions, and the intersections of these bearings locate the float in a horizontal plane. The ship's position is determined by radar range and bearing from an anchored dan buoy, and the movement of the dan buoy itself is checked by sounding over small but recognizable nearby features on the sea bed.

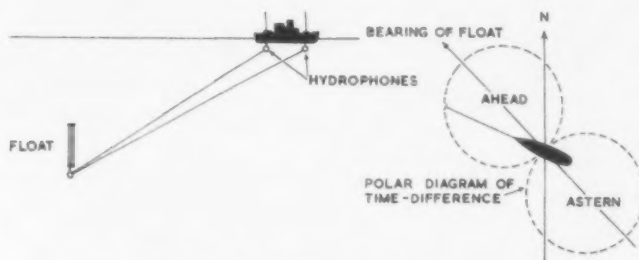


Fig. 3. Method of locating float.

The depth of the float can be estimated each time a bearing of it is taken, from the size of the "figure-eight" pattern obtained when the time-differences are plotted. The ratio of the maximum time-difference observed, (when the ship is heading directly towards the float) to the direct travel-time from one hydrophone to the other, is the cosine of the angle between the horizontal and the ray coming from the float to the ship. The depth of the float can then be found when the horizontal distance between it and the ship is known. The direct travel-time between hydrophones is measured by floating a transmitter on the surface and observing the maximum time-difference at the two hydrophones, as the ship is swung round.

To avoid errors in bearings and in the time-differences, the hydrophones are kept fairly shallow (about 7 m) and are weighted to prevent their cables from straying too far from the ship's side.

OBSERVATIONS

Of the six floats used during the May-June (1955) cruise of "Discovery II," one was lost in trying out the echo-sounder method of tracking, two others disappeared within a few hours of being released, one developed an electrical fault after 8 hours running, and the other two worked satisfactorily. No explanation can be offered for the loss of two of the floats, though it may possibly have been due to undetected flaws in the tubes causing the compressibility to be higher than the calculated value.

The track followed by one of the floats is shown in Fig. 4, together with the positions of the dan buoy used as a reference mark. These are plotted relative to the southern end of a submarine ridge, rising about 200 m above the surrounding plain. The sides of the ridge are quite steep, and the depth to the plain is 5,330 m. Trouble was experienced with the dan buoy dragging its sinker along the sea bed, and the interpolation between successive fixes is uncertain, so that only the average drift can be determined. This is 5.7 cm/sec, in the direction 250° (true). The float was loaded to sink to 900 m, and estimates of its depth ranged from 800 to 1,500 m.

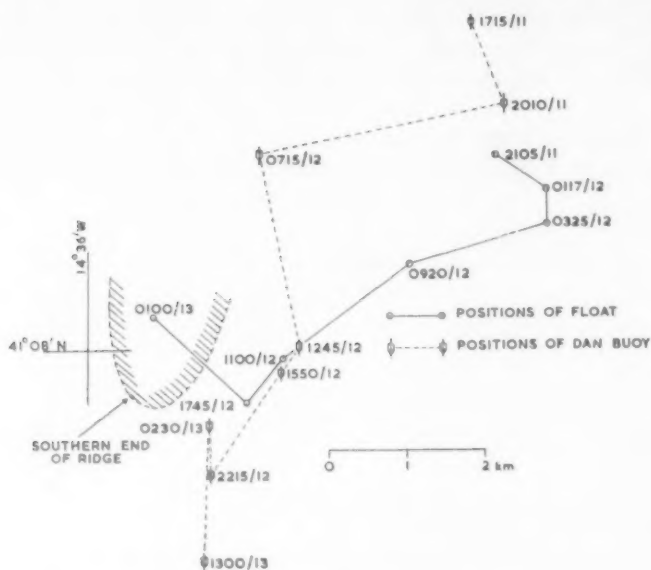


Fig. 4. Track of float, 11th-13th June, 1955.

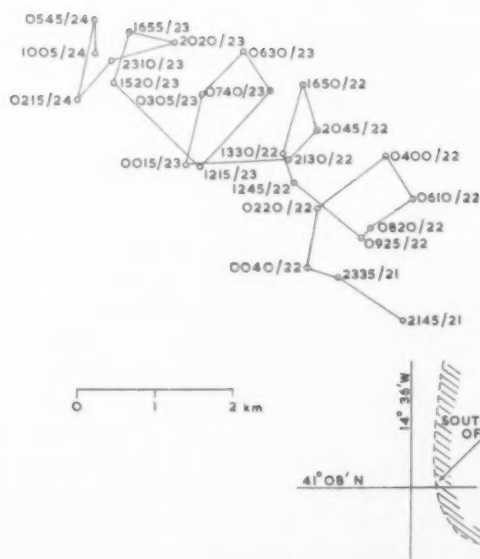


Fig. 5. Track of float, 21st-24th June, 1955.

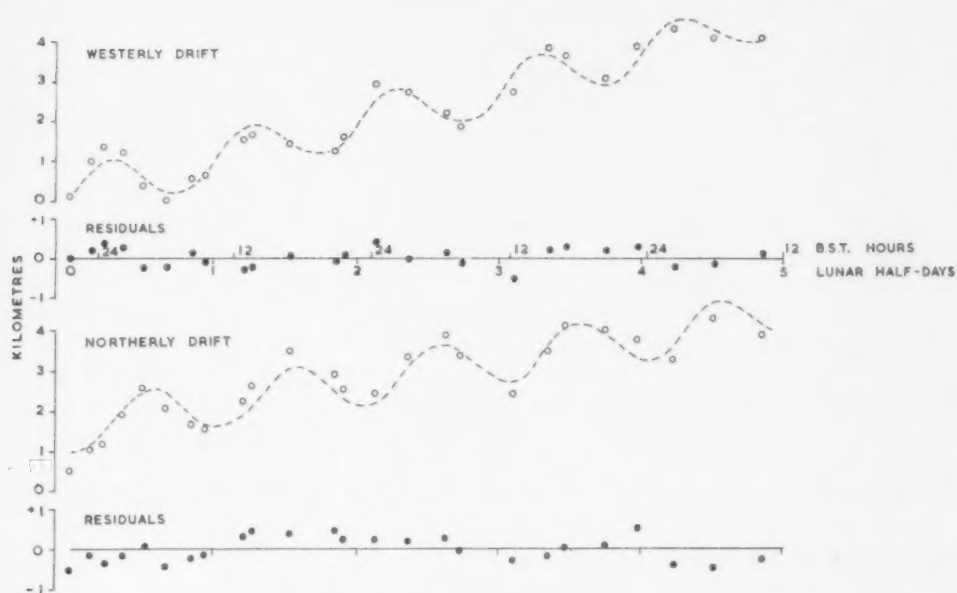


Fig. 6. Northward and westward movements of float plotted against time.

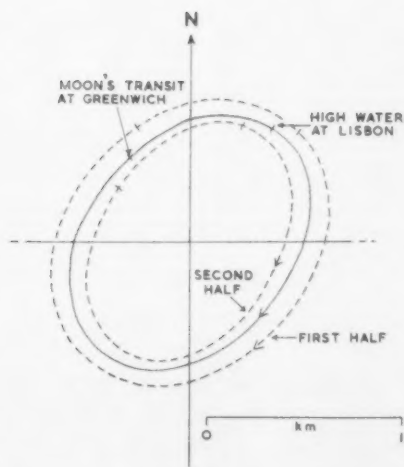


Fig. 7. Tidal components of displacement combined to form an ellipse.

Another float, loaded for 400 m depth, followed the track shown in Fig. 5. More frequent fixes were made, and the dan buoy was more securely anchored, so that tidal oscillations can be seen superimposed on the drift.

The northerly and westerly displacements of the float are plotted against time in Fig. 6. A steady drift plus a lunar semi-diurnal oscillation has been fitted by least squares to each of these, leaving the residuals shown. There is some tendency for the residuals to show an 18-hour fluctuation (approximately the period of inertial oscillations in this latitude) but it is not very significant, since the estimated uncertainty of each observation of the displacement of the float is about ± 0.2 km. Combining the drift components gives a resultant current of 2.4 cm/sec. in the direction 300° (true). The tidal components of displacement are plotted together as an ellipse in Fig. 7. The ratio of the lengths of the axes is 0.73, which agrees fairly well with the theoretical ratio (for an infinite ocean) of 0.68 in this latitude. The direction of the major axis, and the *cum sole* direction of rotation, are also in agreement with theoretical predictions (BOWDEN, 1954). The tidal current, varying from 7.3 to 10.0 cm/sec., is similar in magnitude to those measured by the "Meteor" and "Armauer Hansen" expeditions (DEFANT, 1932; EKMAN, 1953).

To estimate the uncertainty of fitting these tidal oscillations, the observed displacements have been divided into two groups and separate fittings made. The results are shown as the dotted ellipses in Fig. 7.

The depth measurements show considerable scatter (Fig. 8), with a mean value of

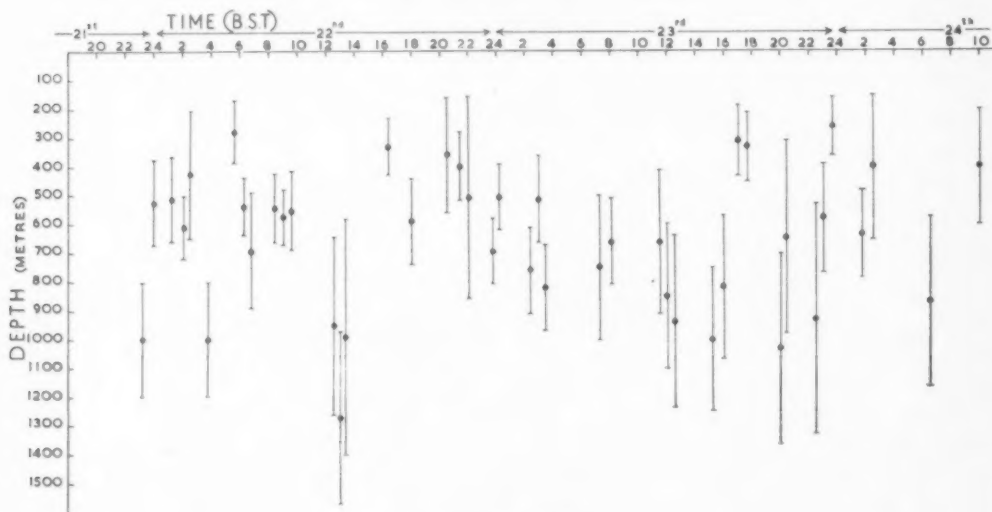


Fig. 8. Depth estimates.

about 600 (± 200) m. The observations are too uncertain to show whether any genuine depth oscillations occurred, but they are sufficient to demonstrate that the sinking rate, after the first few hours, is very small.

ACKNOWLEDGEMENTS

The author wishes to express his thanks to many colleagues in the laboratory,

and in "Discovery II," who took part in the construction of the apparatus and in the experiments at sea. The assistance of the Chief Scientist and members of the staff of H.M. Underwater Detection Establishment, Portland, in making the acoustic signalling equipment, is gratefully acknowledged.

National Institute of Oceanography, Wormley, Godalming.

REFERENCES

- BOWDEN, K. F. (1954), *Deep-Sea Res.* **2**, 33-47.
B. S. 1476 (1949), Wrought Aluminium and Aluminium Alloys. *British Standards Institution*.
B. S. 1500 (1949), Fusion-Welded Pressure Vessels. *British Standards Institution*.
DEFANT, A. (1932), "*Meteor*" reports. Bd. VII. 1 Teil.
EKMAN, V. W. (1953), *Geofys. Publik.* **XIX**, (1).
NEWMAN, F. H. and SEARLE, V. H. L. *The General Properties of Matter*. Arnold & Co., London. 4th ed. 1948, p. 122.
STOMMEL, H. (1955), *Deep-Sea Res.* **2**, 284-285.
ZUBOV, N. N. and CZHIRIN, N. J. *Oceanological Tables*. Moscow, 1940.

A new theory of Caribbean bottom-water formation

L. V. WORTHINGTON

Abstract—A recent section across the Caribbean Sea shows that in the Caribbean deep water oxygen values have dropped 0.3 ml/l in the last twenty years, a loss closely corresponding to that in the North Atlantic deep water. Study of the surrounding Atlantic water suggests that the Caribbean deep water has not been renewed since the end of the eighteenth century, coincident with a cold climatic variation at high latitudes in the North Atlantic. It is further deduced that the Windward Passage was the sill over which this water originally came from the Atlantic, and that both the Jungfern and Windward Passage sills must be considerably shallower than DIETRICH's (1939) estimates.

SINCE 1933-1937, when the principal oceanographic surveys of the Caribbean Sea were carried out (PARR, 1937, 1938) changes have taken place which throw some doubt on the system of Caribbean bottom-water formation described by DIETRICH (1939), and in fact on the location and depth of the sill over which, in his view, this water flowed. In presenting new hypotheses on these matters the present author is at a great advantage over earlier authors in that they were limited to virtually synoptic data as far as the deep water is concerned, whereas he has access to observations made after a lapse of twenty years, when the changes which take place continually are thrown into bold relief.

The new data take the form of a hydrographic section which was made in the *Atlantis* in December, 1954. This section was planned in order to repeat one of PARR's sections which he made across the Caribbean Sea in March, 1933. The station positions of both these sections are plotted in Fig. 1. Before presenting the changes which have occurred, a brief description of the Caribbean deep water will be given together with DIETRICH's theory as to its formation.

In the Caribbean Basin the temperature diminishes with increasing depth to a minimum of 4.03° to 4.09° at about 2,250 m. Below this minimum the temperature rises slowly towards the bottom at a gradient slightly less than adiabatic. The water below the temperature minimum has a salinity of between 34.97‰ and 34.99‰ and can be regarded as a single water type. DIETRICH showed that the potential temperature of all the deep water varied between 3.81° and 3.85° , a value nearly 2° higher than that of the surrounding North Atlantic deep water. He considered that the Jungfern Passage was the deepest path of communication between the Caribbean and the Atlantic, and that Caribbean deep water flowed over this sill into the basin. Immediately outside the Jungfern Passage water with a potential temperature of 3.81° (the Caribbean minimum) was found at a depth of 1,600 m, and this was the sill depth he assumed, the colder Atlantic water below this level being cut off from the Caribbean Basin. None of DIETRICH's conclusions could be seriously disputed if the deep water in the Caribbean had remained unchanged.

The principal change which has taken place is the loss of oxygen in the deep water. SEIWELL (1938) gave average values of oxygen in the deep water for the whole

Caribbean Basin. These values are summarized below together with the averages for the recent section.

Table 1. *Oxygen concentration at various depths below the temperature minimum in the Caribbean Basin.*

Depth, m	Dissolved oxygen, ml/l		
	1933-4	1954	Loss
2,500	5.10	4.77	0.33
3,000	5.10	4.81	0.29
3,500	5.15	4.84	0.31
4,500	5.18	4.92	0.26
Average	5.13	4.83	0.30

The temperature changes which accompany this oxygen loss are extremely small as shown in Table 2.

Table 2. *The average temperatures at various depths from Atlantis stations 1506-1514 in 1933 and stations 5235, 5257-5261 in 1954. Figures in parenthesis are the number of observations.*

Depth, m	Temperature, °C		
	1933	1954	Gain
2,000	4.061 (9)	4.075 (6)	0.014
2,500	4.070 (5)	4.078 (6)	0.008
3,000	4.118 (5)	4.122 (5)	0.004
3,500	4.167 (3)	4.172 (5)	0.005

Below 3,500 m the data are insufficient for an average, but in no case does the temperature at any level vary by more than 0.01° between the years. Since the thermometers are only accurate to this amount, nothing can be said about the very deep water until sufficient new observations have been made elsewhere in the Basin. The small gains in temperature above the 3,000 m level do appear to be significant, and are evidently the result of eddy diffusion from higher levels.

The rate of oxygen consumption of 0.3 ml/l in twenty years (0.015 ml/l-year) has certain implications which bear discussion. If the temperature and salinity of a water type are known, its oxygen saturation point is also known. If the oxygen consumption rate in this water type has remained unchanged since the time of saturation, a date can be assigned to its last renewal by contact with the atmosphere. This method of dating is somewhat crude, and it is open to criticism in that the initial oxygen consumption due to the immediate oxidization of the organic matter in the water may be at a far higher rate than subsequently (REDFIELD, personal communication). A further objection is that the water may not have been fully saturated with oxygen by the process of its last renewal. If either of these objections is valid, a date of last renewal must be moved into the more recent past, so that the method at least sets a time limit before which the last renewal should not be

supposed to have taken place, since there is no reason for thinking that the rate of consumption has become more rapid.

The deep-water consumption rate of 0.015 ml/l-year is identical to that estimated by WORTHINGTON (1954) for the North Atlantic deep water. His estimate was a fairly rough one due to the paucity of recent data. Now that numerous samples have been obtained from the depths of the Caribbean, which are filled with nearly homogeneous water, perhaps a consumption rate of this magnitude can be more widely relied upon. Doubtless the rate is not the same throughout the oceans, but varies with the locality, since the supply of organic matter from the upper layers will not remain constant in different areas.

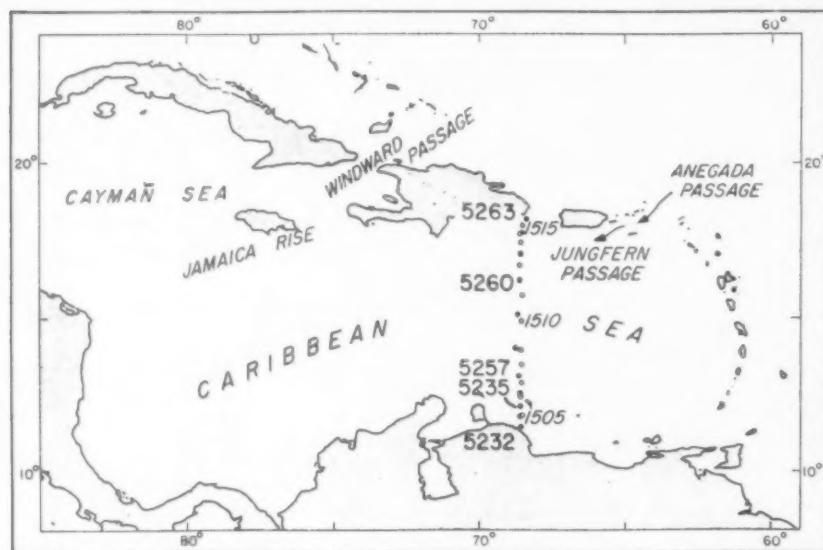


Fig. 1. The Caribbean and Cayman Seas, including the principal sills. Two *Atlantis* sections are plotted, one from 1933 and the other from 1954.

In his estimate of the age of the North Atlantic deep water WORTHINGTON used the following figures:

Average O_2 in 1930 = 5.8 ml/l. From SEIWELL's (1934) chart of O_2 at 2,500 m.

Average O_2 in 1950 = 5.5 ml/l. From *Atlantis* stations in the years 1947-1954. This gave the rate of 0.015 ml/l-year.

Saturation point of the water = 7.6 ml/l. It was assumed that the water had a temperature of 2° and a salinity of 34.9‰ at the time of its formation.

Subtracting $7.6 - 5.8 = 1.8$ ml/l of oxygen consumed between the saturation date and 1930.

1.8 ml/l at 0.015 per year = 120 years prior to 1930.
= 1810.

A coherent dating system can be arrived at for the Caribbean and Cayman Seas by using this consumption rate, a system, moreover, which is consistent with what is known of the climatic variation at high latitudes. No recent observations have been obtained in the Cayman Sea, and it will have to be assumed that the rate of 0.015 ml/l holds true there. In the chronology which follows we are dealing with the history of a single water type: $T = 4.0^\circ$, $S = 34.98\text{‰}$. The oxygen saturation-point of this water is 7.25 ml/l (using the potential temperature of 3.8°). The last renewal of this water in the North Atlantic is the latest date in the chronology, and the dates which are of the greatest concern are those at which the basins became isolated from each other and from the Atlantic. Dates are rounded off to the nearest decade; oxygen values are in ml/l.

- 1790 The 4.0° isotherm drops below the threshold at the Jamaica Rise. Deep water communication between the Cayman and Caribbean ceases. (O_2 in the Caribbean Sea in 1933 was 5.13 from Table 1, $7.25 - 5.13 = 2.12$ consumed. At $0.015/\text{yr} = 142$ years prior to 1933.)
- 1810 Last renewal of North Atlantic deep water (from WORTHINGTON).
- 1840 The 4.0° isotherm drops below the threshold at the Windward Passage. Deep water communication between the North Atlantic and the Cayman Sea ceases. (O_2 in the Cayman Sea in 1933 was 5.85, from SEIWELL, 1938. $7.25 - 5.85 = 1.40$ consumed. At $0.015/\text{yr} = 93$ years prior to 1933.)
- 1850 The 3.8° isotherm loses contact with the atmosphere at high latitudes. (O_2 of this water outside the Windward Passage was 5.95, from SEIWELL, 1938. $7.25 - 5.95 = 1.30$ consumed. At $0.015/\text{yr} = 87$ years prior to 1933.)

This chronology is strongly supported by climatological evidence. AHLMANN (1948) summed up a vast mass of data of many kinds (glaciological, eustatic, biological, etc.) which all confirm that a remarkably cold period centred around the end of the eighteenth century. This can be most clearly illustrated by the temperature data from Holland, which extended back to the beginning of the eighteenth century. AHLMANN's January and July average temperatures (30-year overlapping means) are reproduced here (Fig. 2). There is much glaciological evidence that this is not merely a local phenomenon. AHLMANN in fact suggests that the glaciers in the North Atlantic area reached their greatest point of advance since the Würm/Wisconsin ice age in the middle or late eighteenth century.

If this system of deep water formation is accepted, there is no further need for assuming that the Jungfern Passage is the sill for the Caribbean basin and thus for accepting the coincidence that the sill-depth waters flowing through the Jungfern and Windward Passages, which are 750 km distant from each other, differ by not as much as 0.01‰ in salinity and by only 0.04° in potential temperature. If the concept of the steady state is held to, it is impossible to supply the Caribbean Basin from any other source since, in 1933, at any rate, the same temperature minimum was found at greater depths in the Cayman than in the Caribbean Basin. The close similarity between the two water types on either side of the Jamaica Rise supports the conclusions that the Caribbean deep water was originally supplied from the Cayman Sea, and that the Windward Passage was the ultimate sill over which the water of both basins poured in from the Atlantic.

The isolation of the Cayman deep water from the Atlantic occurs at 1840 in this chronology, some years subsequent to the period of greatest cold at high latitudes. This occurrence can be attributed to the gradual weakening of the North Atlantic eddy. This weakening, according to the geostrophic equation, should be accompanied by a rise in the level of the thermocline at the centre of the eddy, and a drop in level around the edges. In 1954 the Woods Hole Oceanographic Institution undertook a new oceanographic survey of the western North Atlantic in repetition of the survey

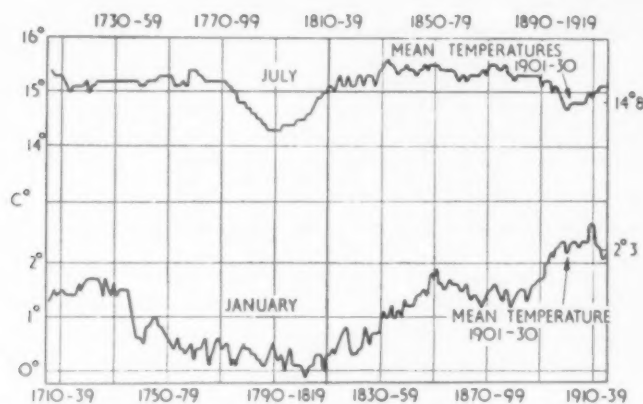


Fig. 2. January and July temperatures in Holland plotted in 30-year overlapping means. Reproduced from AHLMANN (1948).

made between the years 1922-1934, principally by the research vessels *Dana* and *Atlantis*. While it would be premature to give detailed results until the new survey is nearer completion, there is abundant preliminary evidence that the eddy has weakened since that period. This evidence comes in many forms; among them are an average drop of 10 per cent in the computed volume transport of the Gulf Stream off Woods Hole, the further advance of the Mediterranean water into the Sargasso Sea, and on one section at least (Bermuda to Hispaniola) just such changes in the depth of the thermocline as are described above, and as would cause the 4° isotherm to drop even further below the sill depth at the Windward Passage. This weakening of the eddy is related to the amelioration of the Arctic climate.

It is implicit in the reconstruction of events presented here that the sill depths of both the Jungfern and Windward Passages must be considerably shallower than those assumed by DIETRICH (both 1,600 m) in order to permit steady flow. No one has yet established by actual sounding the depth of any of the important sills which connect the various basins of the American Mediterranean Sea to each other and to the Atlantic.

If the Windward Passage were to be sounded thoroughly, a simple matter with the continuously recording sonic equipment available today, one could determine the amount that the 4° isotherm has subsided below the sill depth since the days when free communication took place between the Cayman deep water and the Atlantic. By such means as this, a beginning could be made towards estimating the

volume transport of the North Atlantic Eddy at the time of its most vigorous circulation.

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REFERENCES

- AHLMANN, HANS W : SON (1948), The present climatic fluctuation. *Geogr. J.*, **112** (4-6), 165-195.
- DIETRICH, GÜNTER (1939), Das Amerikanische Mittelmeer. *Z. Gesellsch. Erdkunde*, **1939**, (3-4), 108-130.
- PARR, ALBERT E. (1937), A contribution to the hydrography of the Caribbean and Cayman Seas, based upon the observations made by the Research Ship *Atlantis*, 1933-1934. *Bull. Bingham Oceanogr. Coll.*, **5** (4), 1-110.
- PARR, ALBERT E. (1938), Further observations on the hydrography of the eastern Caribbean and adjacent Atlantic waters. *Bull. Bingham Oceanogr. Coll.*, **6** (4), 1-29.
- SEIWELL, H. R. (1934), The distribution of oxygen in the western basin of the North Atlantic. *Pap. Phys. Oceanogr. Meteorol.*, **3** (1).
- SEIWELL, H. R. (1938), Application of the distribution of oxygen to the physical oceanography of the Caribbean Sea region. *Pap. Phys. Oceanogr. Meteorol.*, **6** (1), 1-60.
- WORTHINGTON, L. V. (1954), A preliminary note on the time scale in North Atlantic circulation. *Deep-Sea Res.*, **1** (4), 244-250.

NOTE

This paper was referred to DR. L. H. N. COOPER of the Plymouth Laboratory, who has recommended its publication. He writes "Some of WORTHINGTON's opinions and conclusions differ radically from mine. In such a complex subject as this is, the truth is likely to be reached only by successive approximation. It would profit no one to defer publication pending agreement between us. Only more firm facts can achieve such agreement. Again the bases for my opinion have not been published and some of them cannot be for some time."

Lateral eddy viscosity in the Gulf Stream system

HENRY STOMMEL

(Received 16 August, 1955)

RECENTLY (FOFONOFF, 1954 ; STOMMEL, 1955) attention has been called to the inertial properties of the Gulf Stream. A new inertial boundary layer theory of the Gulf Stream (Morgan, 1955 ; Charney, 1955) has been offered as an alternative to the earlier (MUNK, 1950) viscous boundary layer theory. In his original attempt to fit the viscous theory to the Gulf Stream, MUNK (1950) chose a representative width of 200 km, which led to a coefficient of lateral eddy viscosity of $5 \times 10^7 \text{ cm}^2 \text{ sec}^{-1}$. The recent detailed cross-sections by WORTHINGTON (1954) indicate an instantaneous width of less than 100 km, corresponding to coefficients of lateral eddy viscosity of somewhat less than $5 \times 10^6 \text{ cm}^2 \text{ sec}^{-1}$. In this case, however, the inertial terms are no longer negligible, even in the viscous boundary layer theory, and the inertial boundary layer theory seems to give a good representation with vanishing friction. It has become important, therefore, to make an independent measurement of the lateral eddy viscosity on a scale appropriate to the instantaneous width of the Gulf Stream, in order to decide whether the inertial or the viscous boundary layer theory is the better description of the dynamics of the Stream.

The literature does not contain current measurements at any place in the Stream, well removed from the coast, sufficiently detailed to permit computation of lateral Reynolds stresses, but I have found, in the original log books of Pillsbury, deposited in the archives of the U.S. Coast and Geodetic Survey, 633 consecutive surface current measurements made at fifteen minute intervals during a week-long anchor station of the *Blake* in 200 fathoms, 8 miles off Fowey Rocks in the Florida Straits. This is the region of strong cyclonic shear (about 10^{-4} sec^{-1}) to the west of the axis of maximum velocity.

The computed eastward u and northward v components (magnetic) of the measured velocities are plotted in Fig. 1, and also the product uv . Since the mean Stream is very nearly due north, the turbulent flux of momentum per unit area F to the eastward is approximately $\rho (\overline{uv} - \bar{u} \bar{v})$, where the bar signifies a time mean over a large number of observations.

The probable errors of measurement can only be guessed at, after all these years (the measurements were made in 1885). Details of how the measurements were made may be found in PILLSBURY'S summary paper (1890). On the basis of current practice we may suppose that the probable error in direction of a single measurement is $\pm \frac{1}{4}$ points (± 3 degrees), and that the probable error of the speed measurement (current pole) is ± 0.1 knots. Because the current is always so nearly northward, the error in u is mostly due to errors in direction, and that in v mostly due to errors in speed. Both probable errors amount to about ± 0.1 knots. The probable error of each product uv is taken as ± 0.2 square knots. The probable error of various means of n observations is taken as $(n)^{-\frac{1}{2}}$ that of individual errors, and the value of F/ρ for all 633 observations is -0.034 ± 0.016 square knots. When one plots

the consecutive values of uv , as in Fig. 1, he sees that there is a tendency for large persistence from one time to another; values of same sign tend to occur in blocks of 2 to 16 hours' duration. This suggests the possibility of large sampling errors in the above computations. As a check, the first 592 observations have been divided

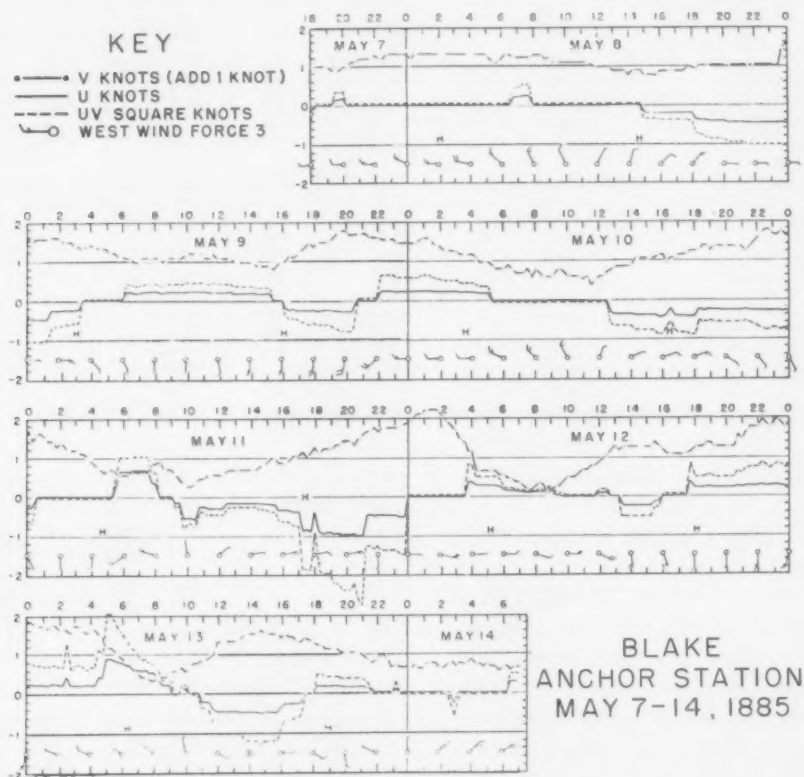


Fig. 1. Eastward (u) and northward (v) components of the surface velocity as observed every fifteen minutes starting at 1800 LCT, 7 May, 1885, by the *Blake*, Lt. J. E. PILLSBURY commanding, eight miles off Fowey Rocks in the Florida Current. The product uv is also shown. The time of high water (tide) observed at Fowey Rocks is marked by H. The winds as recorded in the *Blake* log are also indicated according to standard symbols. A different origin is used for v . Units of u and v are knots, for uv , (knots)².

into four equal sub-groups, and values of F/ρ computed separately; and an additional group of 306 independent observations of a later date is also exhibited in Table I. A comparison of these variously computed values of F/ρ suggests that the sampling error is negligible, that the computed values of F/ρ tend to cluster about a point slightly less than zero, but almost within the range of error. Corresponding values of the lateral eddy coefficient $(F/\rho)/(\partial \bar{v}/\partial x)$, using $\partial \bar{v}/\partial x = 10^{-4} \text{ sec}^{-1}$, are also tabulated. We see at once that they are much less than the large values quoted above in connection with the viscous boundary layer theory of the Gulf Stream. Thus, although we have made a very bad determination of the actual eddy coefficient in the Florida Current off Miami, we can say that it is probably less than one fifth the minimum value required by the viscous theory, and that the inertial theory is a better description

of the instantaneous Stream in the Florida Straits.

During the week of observation about 700 km of water flowed past the point of observation, so that any eddy-like features with dimensions less than the width of the Stream should be included in the average, unless they are extremely elongated.

Table I. Velocity components, cross-products, Reynolds stresses, and eddy viscosities computed for various samples of the data in the Florida Straits.

Date and time of beginning	No. Obs. n	\bar{u} east knots	\bar{v} north knots	\bar{uv} (knots) ²	$F/\rho = \bar{uv} - \bar{u}\bar{v}$ (knots) ²	Coeff. Eddy viscosity cm ² sec ⁻¹
1885 A.D.						
May 7, 1800 LCT	633	-0.0228	2.1176	-0.0825	-0.034 ± 0.016	9 (± 5) × 10 ⁵
Sub-groups						
May 7, 1800	148	-0.0953	2.008	-0.2160	-0.025 ± 0.034	
May 9, 0600	148	0.0063	2.112	0.0147	0.014 ± 0.034	
May 10, 1900	148	-0.1618	2.086	-0.4019	-0.064 ± 0.034	
May 12, 0800	148	0.1038	2.204	0.1999	-0.029 ± 0.034	
Independent Series						
May 24, 1700	306	-0.2223	2.133	-0.4819	-0.007 ± 0.024	2 (± 6) × 10 ⁵

It should be emphasized that comparable measurements are not available in the regions of cyclonic and anticyclonic shear off Cape Hatteras in the truly "free" Stream, and that therefore the choice between viscous and inertial theory for the Stream as a whole is not settled. The present results do give indication of what we may expect to find, however, and may act as a guide as to how the observations ought to be made.

The very high value of eddy diffusivity (STOMMEL, 1951), which I computed in an analysis of downstream spreading-out of the envelope of fourteen surveys of the inshore edge of the Gulf Stream, was 2.3×10^8 cm² sec⁻¹. I now suspect that this estimate may have been a misinterpretation of the data: the wavy meander-like structures in the instantaneous Stream do not necessarily produce a net cross-stream transport of properties. The frequency of occurrence of detached eddies is not known; and no reliable estimate of cross-stream transport can really be made from the data I used. In any case the scale of turbulence associated with this very high value is too great to permit its use as a process involved in the formation of the instantaneous filament-like Gulf Stream: indeed, this "Gross-Austausch" appears to be produced by the instability and decay of the instantaneous Stream.

Contribution No. 796 from the Woods Hole Oceanographic Institution

REFERENCES

- CHARNEY, J. G. (1955), *The Gulf Stream as an inertial Boundary Layer*. (In press).
 FOFONOFF, N. P. (1954), Steady flow in a frictionless homogeneous ocean. *J. Mar. Res.* 13, (3), 254-262.
 MORGAN, G. W. (in press).
 MUNK, W. H. (1950), On the wind-driven ocean circulation. *J. Meteorol.* 7, 79.
 PILLSBURY, J. E. (1890), The Gulf Stream. *Rep. of the Superintendent, U.S. Coast and Geodetic Survey, App.* 10, pp. 459-620.
 STOMMEL, Henry (1951), Determination of the lateral eddy diffusivity in the climatological mean Gulf Stream. *Tellus*, 3, 43.
 STOMMEL, Henry (1955), Discussion during the Woods Hole Convocation, 1954. *J. Mar. Res.* 14, (in press).
 WORTHINGTON, L. V. (1954), Three detailed cross-sections of the Gulf Stream. *Tellus*, 6, 116.

Book Review

The Sediments of the Western Gulf of Mexico. HENRY C. STETSON, and PARKER D. TRASK. Part I : The Continental Terrace of the Western Gulf of Mexico : Its Surface Sediments, Origin and Development. Part II : Chemical Studies of Sediments of the Western Gulf of Mexico. Papers in Physical Oceanography and Meteorology, Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, Vol. XII, No. 4, 1953. 120 S.

Von der vorliegenden Darstellung der Sedimente aus der westlichen Hälfte des Golfs von Mexiko vor der Küste der Vereinigten Staaten zwischen dem Mississippi-Delta und der mexikanischen Grenze ist besonders der zweite Teil für die Leser dieser Zeitschrift wichtig. Im ersten Teil wird durch HENRY C. STETSON die allgemeine Sedimentpetrographie gegeben, im zweiten Teil behandelt PARKER D. TRASK im ersten Abschnitt den Gehalt anorganischer Substanz in den Lotkernen. Von den besonders für die Erdölgeologie wichtigen Untersuchungen mag hier folgendes erwähnt werden : Der Gehalt an Kohlenstoff ist umgekehrt proportional zur Korngrösse, er nimmt von 0,5% C im Sand bis auf 2% im Ton auf dem Schelf und Kontinentalabhang zu. Im Mittelteil der Tiefsee ist der Kohlenstoffgehalt um etwa 40% geringer. Das Verhältnis C : N ist auf dem Schelf etwa 8, 5 und steigt in der Tiefsee bis auf 9, 5. Im Abschnitt 2 werden 14 Bauschanalysen von Sedimentproben mitgeteilt und daraus Molquotienten berechnet. Der Verfasser spricht selbst aus, dass gesonderte Analysen der groben und feinen Fraktionen und ergänzende mineralogische Bestimmungen die Auswertung sehr erleichtert haben würden. Es ist zu hoffen, dass diese Untersuchungen noch nachgeholt werden. Im 3. Abschnitt wird der Wassergehalt der Sedimente behandelt, besonders die Beziehungen zur Korngrösse.

Beide Arbeiten sind wichtige Beiträge sowohl zur Petrographie der Sedimente wie auch zur Geochemie des sedimentären Bereichs.

C. W. CORRENS

EDITORIAL ANNOUNCEMENTS

New Instruments and Techniques

INTERPRETATION of the scope of the subject matter published in *Deep-Sea Research* has always been broad, but it has had as its prime object the furtherance of knowledge of the deeper parts of the ocean. The editors believe that this prime object might better be achieved by the inclusion of a new section in the Journal containing brief notices, not accompanied by results, of new techniques and instruments. The publication of full instrumental details and working drawings is of limited interest, and beyond the scope of the Journal. On the other hand if, through short notices, the attention of our readers is drawn to the existence of new instruments and techniques, the full details can be obtained directly from the originators.

For this new section the editors solicit paragraphs, which will be published with the names and addresses of the originators.

Editorial Board

MR. C. D. OVEY has been obliged, through extensive outside commitments, to resign from the editorial board and will in future serve on the advisory board. It is with great regret that the editors and publishers accept his resignation, and they wish to thank Mr. OVEY for all the help he has given this journal in its initial stage. It is in no small degree due to him that, after two years' existence, *Deep-Sea Research* is to-day already well established.

Dr. M. N. HILL, Department of Geodesy and Geophysics, Cambridge, has kindly agreed to join the editorial board as editor for the U.K.

Erratum

PAGE 179, Volume 2 : the heading of column 3, Table 3 of the article by BOSTWICK H. KETCHUM, NATHANIEL CORWIN and D. JEAN KEEN on *The significance of organic phosphorus determinations in ocean waters* should read :—

*Total minus inorganic phosphorus
% of samples.*

Geochemistry of the radioactive elements in the ocean

A critical summary

F. F. KOCZY

Abstract—In discussion of the distribution of radioactive elements in the hydrosphere, and the mechanism of the removal of ionium from sea water, different oceanographic conceptions have to be used. The assumptions made by HOLLAND and KULP in two papers dealing with this subject do not appear justified. In the present paper some of the divergences between these authors and European workers in the field are discussed. In order to do this the basic measurements are critically reviewed, and conceptions such as rate of sedimentation, water content of sediment, the estimation of average values, and the constancy of the composition of sea water, are discussed in connection with the geochemistry of the radioactive elements present in the hydrosphere.

Two papers recently published in *Geochimica et Cosmochimica Acta* by H. D. HOLLAND and J. L. KULP, dealing with the radioactive elements present in the ocean, raise questions which call for a discussion of the results these authors have obtained as compared with recent results from the Swedish deep-sea expedition (F. KOCZY, G. KOCZY, V. KRÖLL).

As far back as 1908 J. JOLY found a relatively high radium content in deep-sea sediments. These results were later confirmed through measurements made by H. PETTERSSON (1950), although JOLY's values were generally higher. On the other hand, C. S. PIGGOT in 1933 published radium values lower than those of PETTERSSON. In 1938 EVANS and KIP made new measurements of the radium in deep-sea deposits. In 1937 PETTERSSON suggested, as an explanation of the high radium values found in sediments, that ionium is coprecipitated from sea water. This assumption is supported by the fact that the ratio between the ancestral elements uranium and radium in sea water considerably exceeds the equilibrium ratio. EVANS and KIP in 1938 proposed to study the variations in radium content in the cores, in order to test the uranium precipitation hypothesis put forward by PIGGOT. URRY and PIGGOT, after PETTERSSON, also assumed a precipitation of ionium to take place in the sea, and in 1942 they made attempts to determine the ages of different sediment layers from radium measurements, and also to utilize the values found for determining the rate of sedimentation. PETTERSSON in 1943 critically discussed the results given by URRY. Later URRY, largely in collaboration with PIGGOT, published a number of papers on this subject.

During the Swedish deep-sea expedition of 1947-48, and since, special attention has been paid to the geochemistry of the radio-active elements in the ocean. The main part of this work has now been completed, and the results have either been published or are in the press. The most comprehensive work has been carried out in Göteborg by V. KRÖLL, who has measured about 300 sediment samples from great depths in the Pacific and the Atlantic Oceans. KRÖLL (1954) also proposes a new method for determining the average rate of sedimentation, and criticizes the method used by PIGGOT and URRY (1942). In consequence the whole problem now becomes

much more complex than earlier. Quite recently (1954) PETTERSSON and KOCZY published two papers on radioactive elements in the ocean in a Symposium on Nuclear Geology edited by H. FAUL, in which also a list of references from the literature published before the end of 1953 is given.

The present paper serves to discuss the divergences between American workers (URRY, HOLLAND, KULP), and the European workers (PETTERSSON, KOCZY, KRÖLL, and others) in the field. In the first part basic measurements and estimates are reviewed, further on the assumptions made are analyzed, and finally experiments on base exchange are criticized.

The point where both schools differ is the mechanism of the removal of ionium from sea water. URRY, and with him HOLLAND and KULP, assumes an adsorption on sediment-particles, giving a constant concentration in each type of sediment. Contrary to this, PETTERSSON and co-workers assume a constant rate of precipitation. This discrepancy is already discussed by KRÖLL, who showed that URRY's basic idea of the mechanism of removal cannot hold true, since, on this basis, the distribution of radium would always decrease in depth from the equilibrium point downwards. Another fact also which casts doubt upon the correctness of this assumption is the inverse correlation of radium content and the rate of sedimentation. The only evidence in its favour comes from the investigations of HOLLAND and KULP, who, as will be shown later, seem to have overlooked a source of error in their experiments.

In the calculations such oceanographic conceptions as average value of sedimentation, average water content and average radium content of sediments have to be used. Therefore, the elements for the formation of geochemical averages in deep-sea sediments have to be discussed here. Furthermore, the water content as taken by HOLLAND and KULP from KUENEN (1950) is erroneous, presumably because of a misprint in KUENEN's "Marine Geology," where average water content is given as 50 to 85% of *volume* instead of *weight*. This gives rise to an error of a factor of about 2.5. Also the quotation from RUBEY seems to be due to a misunderstanding. Therefore it appears necessary to discuss these highly complex problems, which fall more within the realm of oceanography than of geochemistry. Calculation of the balance of radioactive elements in the hydrosphere as the result of new determinations will be given in a paper by KOCZY, PICCIOTTO, and POULAERT.

REVIEW OF MEASUREMENTS

The uranium content in sea water has been measured with results varying between 0.8 and 3 $\mu\text{g/L}$. The earlier determinations carried out in Vienna (HERNEGGER and KARLIK) gave an average of 1.3 $\mu\text{g/L}$, fairly independent of locality and depth. Determinations published in 1952 by URRY and E. RONA are in general very variable, and must be considered too low. Recent measurements by NAKANISHI (1952) and by SMITH-GRIMALDIS (1953) give rather higher values, between 1 and 3 $\mu\text{g/L}$. STEWART and BENTLEY give a value of about 2.5 for two Pacific Ocean water samples. Unpublished determinations by HECHT on water from the Baltic Sea range between 0.8 and 5.9 $\mu\text{g/L}$. The general trend of uranium distribution with regard to depth in oceanic environment is the same according to NAKANISHI's determinations as for KOCZY's except that NAKANISHI's values are higher by a factor of two; the surface

values are low and a maximum is shown to occur at about 1,000 m depth. HOLLAND and KULP are using 3×10^{-9} g/ml, but we propose a value of $2 \pm 1 \times 10^{-9}$ g/ml.

As a possible explanation of the discrepancies between the uranium values for ocean water found by KARLIK *et al.* and by workers in the U.S.A. and elsewhere, a difference in the uranium standards used has been suggested. Professor BERTA KARLIK, director of the Institut für Radiumforschung in Vienna, has proposed that an exchange of standards between Vienna and Columbia should be made in order to ascertain whether this source of error has influenced the results. During the correspondence with Dr. H. FAUL I proposed also that the sampling technique and the treatment of the samples, as carried out by the Water Branch Laboratory of the U.S. Geological Survey on the one hand and the laboratories of the Oceanographic Institute in Göteborg and Institut für Radiumforschung in Vienna on the other, should be compared. *The uranium content of deep-sea sediments*, calculated to carbonate content zero, is found by URRY (1941), and also by HECHT and KRÖLL, to vary between 1 and 3 μ g/g.

For the radium content of sea water, values have been given varying between 0.3 to 3.0×10^{-13} g/L by American and European workers. The average given by EVANS and co-workers of 0.8×10^{-13} was confirmed by the determination of samples taken by the Swedish deep-sea expedition. The distribution with depth shows in general a distinct minimum at about 500 m (0.4×10^{-13} g/L) and increasing values towards the bottom. As an average we may take $0.8 \pm 0.5 \times 10^{-13}$ g Ra/L. There is no reason to take 0.3×10^{-13} g Ra/L as an average, as HOLLAND and KULP have done.

The radium content in sediments varies between 0.3 and 67×10^{-12} g Ra/g, i.e. between extremely wide limits. The distribution with depth in the sediments shows a maximum near the surface and often also a secondary maximum at somewhat greater depth (30-50 cm in Pacific red clay); from these measurements it is of little use to calculate an average unless specific assumptions are made regarding the concentration of radium in deep-sea sediments.

Ionium determinations in sea-water, which have recently been commenced, indicate a very low concentration, less than 2×10^{-13} g Io/L (KOCZY, PICCIOTTO, POULAERT and WILGAIN).

The ionium content (PICCIOTTO and ISAAC) in the sediment near the surface of Pacific red clay is higher than 2×10^{-9} g Io/g, and shows a decrease with depth.

OCEANOGRAPHIC CONCEPTS

The rate of sedimentation seems to be variable with time and locality. Usually it is expressed in thickness formed per time unit, but the variable water content (40 to 85 weight per cent) makes the results unsuitable for geochemical calculations. If possible it should be expressed in g/m² year or in similar units (KOCZY, F., 1950, 1951; ARRHENIUS, 1947, 1952). For that purpose, HOLLAND and KULP use as average water content 65 per cent of volume, and arrive at the conclusion that 1 ml wet sediment corresponds to 1 g dried sediment, but the water content is about 65 per cent of weight as the determinations of *Meteor*, *Snellius* and *Albatross* samples have shown (CORRENS, 1935; KUENEN, 1935; ARRHENIUS, 1952). KOCZY (1951) has given a theoretical formula applicable for the estimation of the dry weight of 1 ml wet

sediment :

$$S = \frac{\rho_w \rho_s}{\rho_w + \frac{p}{100 - p} \rho_s} \quad \text{g/cm}^3$$

where ρ_w = density of water, ρ_s = density of dry sediment, p = water content in percentage of weight. ARRHENIUS has criticized the theoretical approach and determined the conversion factor by experiments. He obtained the following formula:

$$S = \frac{1}{0.01028 W + 0.368} \quad \text{g/cm}^3$$

where $W = \frac{p}{100 - p}$ = water content of wet sediment in percentage of sediment dried at 20°C. A fact not pointed out by ARRHENIUS is the identity of both formulae, if for ρ_s is put 2.7 and for ρ_w 0.974. Furthermore, by recalculating to sediment dried at 105°C, ρ_s becomes 2.64 and ρ_w 0.994. The error made by using 1.00 for ρ_w and 2.60 for ρ_s is less than 2 per cent. A better agreement could not have been expected.

Table 1, giving the conversion factor for different water contents, shows clearly how strongly the conversion factor depends on the water content.

Table 1

p	W	S
100		0.00
90	900	0.104
80	400	0.224
70	233	0.362
60	150	0.526
50	100	0.716
40	67	0.947
30	43	1.234
20	25	1.60
10	11	2.08
0	0	2.70

Present methods for the determination of the actual rate of sedimentation are either based on palaeontological data or on radio-active measurements. The palaeontologist attempts to establish a co-ordination between different layers and climatic variations. The degree of uncertainty is, however, very great. Also, the radioactive methods are also based on assumptions which cannot always be proved. The determinations by W. SCHOTT (1933) on material from the *Meteor* expedition is uncertain by a factor of 2 to 1. KOCZY has shown that the distribution is log-normal, the limits being 1 to 16 g/m² year; the arithmetic mean is about 5 g/m² year. ARRHENIUS gives for the Pacific Ocean a value of 0.7 g/m² which he assumes to be a constant for the region investigated. His value was obtained by the radio-carbon-dating method (ARRHENIUS, KJELLBERG and LIBBY, 1951). All these values given refer to the mineralogical component of the sediment, which is supposed to be of identical origin (CORRENS, 1935, 1937) and for that purpose they have been

re-calculated to carbonate content zero. ARRHENIUS has corrected his values, not only for the organic lime content but also for the content of silica of organic origin. The variations in the sedimentation rate of carbonates (*Globigerina* ooze) are very high, as the content in the sediment ranges between nought and 98 per cent lime. For the *Meteor* samples, KOCZY, using SCHOTT's values, could determine the arithmetic mean to be 7.7 g/m² year, which represents the average of the net carbonate sedimentation with regard to the solution of lime by the bottom water, in the equatorial part of the Atlantic Ocean. Which of the values here given should be considered representative is open to discussion, but it seems obvious that the rate of sedimentation is higher in the Atlantic than in the Pacific by a factor of about 5 to 1.

An estimation of average values for the removal of radioactive elements from ocean water is highly uncertain, since only few values are known, where both the sedimentation rate and the content of the radioactive elements have been determined. From the general theory of statistics given in all textbooks (CRAMÉR *inter al.*) it follows that the mean value of a product of two *stochastic* variables which show a correlation, must not be formed by the product of the mean values of the two factors. This, according to the present author, is one of the errors committed by HOLLAND and KULP. On the other hand, as long as it is not proved that it can be done, no value for the rate of sedimentation should be used which has been determined from the decay of ionium, since this implies assumptions of the mechanism of the ionium precipitation. The correct mathematical treatment is as follows. If c_i denotes the ionium concentration and r_i the rate of sedimentation, the precipitation of ionium is $c_i r_i$ of the sample (i).

The arithmetic mean $\bar{c}r = \frac{1}{n} \sum c_i r_i$

The value $\bar{c}r = \frac{\sum c_i}{n} \times \frac{\sum r_i}{n}$

The condition for $\bar{c}r = \bar{c} \bar{r}$ is that $c_i = \text{constant} = \bar{c}$ or that $r_i = \text{constant} = \bar{r}$. If on the other hand the correlation exists:

$c_i r_i = A$, it follows that

$$\bar{c}r = \frac{A}{n^2} \sum \frac{1}{r_i} \sum r_i$$

an expression which is always greater than A , if r_i is not constant. But in cases where the rate of sedimentation varies, $\bar{c}r$ necessarily increases with the deviation. It seems now to be a fact that the ionium content is high in samples of a low rate of sedimentation (Pacific Ocean), and low where the rate of sedimentation is high (Atlantic Ocean). The rate of sedimentation and the calculation of the mean values as carried out by KULP and HOLLAND cannot be correct, as they imply that the ionium content and the rate of sedimentation are constant for each type of sediment.

A correct method of calculation would be as follows. For as many samples as possible the rate of sedimentation should be determined by palaeontological methods, and on the same samples the ionium content should also be measured. By the formation of the product of each pair of determinations the rate of the removal of ionium is calculated for each sample separately. Only thus can an average be formed by calculating the arithmetic mean of these products.

The constancy of the composition of sea water has often been discussed (KALLE, 1943; RUBEY, 1951; CONWAY *et al.*, 1951) but it has never been proved for all constituents. This is not the place to discuss the whole complex problem, but some facts concerning the chemistry of radioactive elements must be stressed. Elements and their compounds present in the ocean have either attained saturation or have not. In the first case they should, after having reached saturation, be found in a constant concentration. In the opposite case their concentration may be increasing with time, unless some mechanism exists removing the elements from sea water. The first case is represented by calcium carbonate, which is found under the prevailing CO_2 -pressure to be near to saturation. It is oversaturated in the surface and in deep water 95 to 100 per cent saturated. Sodium chloride, the main salt, seems to vary from one place to another to a very small extent only. Consequently its concentration could increase slowly with time. Chemical processes going on in the ocean are dominated by the biological process but, on the other hand, marine-life is also influenced by the distribution of chemical compounds. Elements and compounds participating in these chemical processes of reduction and oxidation by organisms show a typical distribution with depth, since only the upper 800 m and the bottom layer are populated to any extent. Compounds belonging to this group are phosphates, nitrates, silica, and also those of uranium and radium. Thus the question of the constancy of the concentration is related to the question of life conditions and the redox-potential in the ocean during geological time. All indications point to a great variability of life with climatic variation. Hence the assumption of a constancy to within 20 per cent in 10^7 years seems appropriate for calcium carbonate (RUBEY), but not for the radioactive elements (except ionium (KOCZY 1954). It is very difficult to make an estimate of the factor by which the concentration may have varied. It may be stated to be about 3; but this figure is given with great reserve.

The extraction of radioactive elements by shells seems to be a fact which also indicates the effect of life processes on the composition. Uranium is found in considerable amounts in black shales, as for example in the dyctyonema shales which are found on land from Russia over Sweden to Scotland, in which also the mineral Kolm, rich in uranium, is found. Thorium seems, on the other hand, to be correlated with the hydrolites and the same should be the case for ionium, which is an isotope of thorium, but has so far not been reported since it can only be detected in recent formations.

The determination of the rate of sedimentation by means of the decay of the precipitated ionium, as used by PIGGOT and URRY on the one hand and by H. PETERSSON on the other, involves the assumption of a constant uranium content in sea water: an assumption which, as we have seen, is still under discussion. Both have to make additional assumptions about the mechanism of the incorporation of ionium in the sediment. That is where the difference arises. URRY assumed that ionium is adsorbed in constant concentration on clay, whereas PETERSSON made the assumption that it is precipitated at a uniform rate according to the rate of its production from uranium. The method of URRY and PIGGOT is discussed by KRÖLL, who shows that the distribution of radium with depth in sediment cores of uniform composition cannot be explained by assuming a constant concentration. In particular it is impossible to explain, by URRY's hypothesis, the secondary maxima of radium-content below the sediment.

However, the total content of ionium in the sea water and in the sediment should be in equilibrium with the uranium content of sea water and sediment. Since the uranium content of the sediment is quite low compared with the ionium content, the total excess of ionium in the sediment should be in equilibrium with the uranium in sea water. By assuming an average depth of 4,000 m and using the Ra-values obtained by KRÖLL, the uranium-content of sea water can be calculated. The result seems to agree with the measured values of 1 to 3 10^{-6} g/L. It is very remarkable that the calculated ionium precipitation which corresponds to the total uranium content only shows variations up to 50 per cent, whereas the rate of sedimentation as well as the ionium content given as concentration in the clay varies by a factor of three to four, calculated for the present rate of precipitation. Thus it may be concluded that thorium has reached saturation in the ocean. This clearly shows that the rate of precipitation of ionium is rather independent of the rate of sedimentation.

A further point supporting the correctness of the assumption of a more or less constant rate of ionium precipitation is the fact that it is not necessary to assume great surplus of ionium derived from the river water.

By this method also an average rate of sedimentation can be obtained for the last 300,000 to 400,000 years. The necessary assumptions have been discussed by KOCZY and KRÖLL (1956). The calculation gives slow rate of sedimentation and high ionium concentration in the Pacific red clay.

For the reasons set out above it is unlikely that the measurements made by KULP and HOLLAND can serve as an explanation of the mechanism of the removal of ionium. Theoretically (SCHUBERT) the distribution coefficient at base exchange should be constant for low concentration of ions:

$$K_d = C \frac{v}{m}$$

where K_d = distribution coefficient; C = the ratio of adsorbed ion to part left in solution, v = volume of solution, and m = mass of exchanger (clay). But for radio colloids this does not hold: K_d becomes variable with v/m , but here C is constant over a wide range of v/m values. Chemical considerations indicate that thorium and its isotope ionium, because of their tendency to become hydrated, are present as colloids, whereas radium and its isotope ThX are more likely to be present in true solution in sea water. The results of KULP and HOLLAND do not agree with these considerations. The explanation of the disagreement may be found in the experimental technique used. Here it may also be noted that the geochemistry of the total thorium is not at all discussed in their paper.

SOME OBJECTIONS TO THE EXPERIMENTS OF KULP AND HOLLAND

These collaborators measured the $\beta - \gamma$ activity of the samples and consequently only the ThB and its fellow products. But they used tracer solutions of RdTh (carrier free?). The tracer solutions themselves, as stated, did not show equilibrium conditions. This point was not further discussed, but the ratio of the initial RdTh and ThX did not appear to be constant, judging from their Table 3. If equilibrium obtained the ratio should have been 190 to 1. But in their experiments it varied between 28 to 1 and 170 to 1.

It is difficult to give an explanation of their results without studying the original values, but it is striking that the influence of the emanating power of the samples was *not* considered, nor was the possibility that thoron was occluded on the clay particles. As this effect, discussed by BEERS and GOODMAN (1944), was not considered, and no precautions were taken to control the behaviour of the thoron during their experiments, the results do not lend themselves to an explanation of the mechanism of base exchange.

The thoron, having a short half-life, partly decays in a sediment sample containing ThX; but a part will emanate, and consequently less ThB is measured than would correspond to equilibrium conditions. The diffusion is delayed if the sample becomes thicker, and a greater part of the thoron will decay in the sample, consequently a higher amount of ThB will be found.

Another striking point is the discrepancy in Tables 2 and 3. In the first a concentration of 10^{-4} of sediment is used, giving a distribution coefficient of 2×10^4 for one solution (RT-II) and 1.4×10^4 for another (Mt-1). But in Table 3 all values for a concentration of 10^{-4} g/cc surpass the constancy of K_d giving values of at least 10^5 for Rth and less than 2×10^3 for ThX. It is not stated, whether the activity values of Table 2 were measured after equilibrium conditions had been attained or not, therefore they are not conclusive, because it is not clear if the activity belongs to RdTh or ThX. However, it may be assumed that it belongs to ThX, as RdTh should be adsorbed to 100 per cent on the clay according to Table 3. In this case the results given in Table 2 cannot be used to prove the validity of the law of mass action for RdTh.

CONCLUSIONS

The present author agrees with HOLLAND and KULP in their first conclusion, *viz.* that uranium seems to be enriched in shelf sediments. It may be added, that it appears as if the redox potential is the cause, and that the biological processes play an important part. The enrichment is high where the mineralogical components settle very slowly.

But with regard to ionium and radium one can hardly agree with their conclusions. The rate of extraction of ionium from sea water seems to be of about the same order of magnitude as the rate of decay of uranium, and only a minor part need be assumed to be supplied by river water. The theoretical estimate of the ionium content in sea water is necessarily uncertain, because of the lack of knowledge of the extraction of radium by animals and plants. Only further measurements can be expected to give the correct answer.

The amount of adsorbed ionium calculated by HOLLAND and KULP is lower than the actual content found by PICCIOTTO on surface samples of red clay, *viz.* more than 2×10^{-9} g Io/g. The lower contents of ionium given by PICCIOTTO are found in deeper layers of the sediment, where ionium has decayed to a considerable degree. The discrepancy may be explained by the technique used by HOLLAND and KULP. The possibility of base exchange or adsorption being the cause for the removal of ionium from sea water is admitted (KOCZY, 1949). but the experiments given by HOLLAND and KULP are hardly capable of explaining the mechanism of the removal of ionium and radium from the ocean.

Of the conclusions given by HOLLAND and KULP, the most important seems to be the last, which states that more experimental work is needed before a complete understanding of the economy of the radioactive elements in the Ocean can be reached. Hence, with growing knowledge of the distribution of these elements, of the rate of deposition, and of the chemical processes going on in the Ocean, the aspects will change with time.

Table 2. Contents of, and balance sheet for, radioactive elements in ocean water, calculated for 4,000 m average depth of the ocean and a supply of river water of 8 ml per cm² ocean floor and year.

	g	Contents per ml		Supply to ocean water per cm ² and year by			Removal from ocean water by cm ² and year by	
		ocean	river	decay	river	bottom	decay	sediment
Uranium U ²³⁸	10 ⁻⁹	2±1	1±0.5	0	8	0	0.00015	8
Thorium Th ²³²	10 ⁻¹⁴	4±10	1000±600	0	8000	0	0.0001 (?)	8000
Ionium Th ²³⁰	10 ⁻¹⁷	8±4	100	15000	800	0	72	16000
Radium Ra ²²⁶	10 ⁻¹⁷	8±5	4±2	72	32	1300	1400	0
Mesothorium Th ²²⁸	10 ⁻²⁰	1*	(30?)	40	(100)	40000	40000	0
Radiothorium Th ²²⁸	10 ⁻²¹	3*	—	40000	?	0	40000	6000

* Coastal centres only.

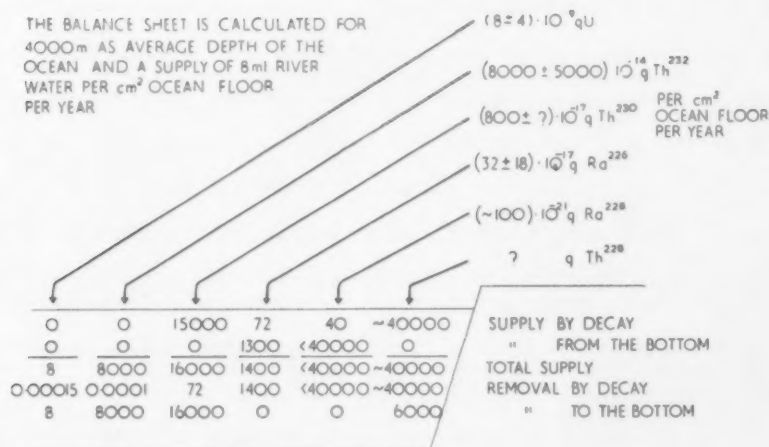


Fig. 1.

A calculation of the geochemical balance sheet after principles similar to those outlined by KULP and HOLLAND was given in a chapter of *Nuclear Geology*, edited by H. FAUL. Since then, attempts to determine the thorium and ionium contents of sea water (KOCZY, PICCIOTTO, POULERT and WILGAIN) have given new upper limits for these elements, and a recalculation was therefore made possible. It seems here to be the proper place to give the new results obtained. The principles of calculation are:

- (1) That the total addition of an element to the ocean, as given by the decay from the mother element and the supply by rivers, equals the decay into the daughter element and the precipitation.
- (2) That the fluctuations in the content of the elements in sea water are negligible for about 1,000 years.
- (3) However, it is assumed that the isotopes are precipitated in the same ratio as their contents in solution are found.

For further details the reader is referred to the original paper. Here the results are given in Table 2 and Fig 1. In the table the measured amounts are denoted by bold face types, the estimates and the calculated values in normal types.

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REFERENCES

- ARRHENIUS, G. (1947), The variety of the glacial clay. *Svev. Geol. Unders. Ser. C.* No. 486.
- ARRHENIUS, G., KJELLBERG, G. and LIBBY, W. F. (1951), Age determination of Pacific chalk ooze by radiocarbon and titanium content. *Tellus*, 3, 4.
- ARRHENIUS, G. (1952), Sediment cores from the East Pacific Ocean. *Rep. Swed. Deep-Sea Exp.*, vol. 5.
- BEERS, R. F. and GOODMAN, C. (1944), Distribution of radioactivity in ancient sediments. *Bull. Geol. Soc. Amer.*, 55, 229-1254.
- BERNERT, T.; (1951), Radiumbestimmungen an Tiefseesedimenten. *Mitt. Inst. für Radiumforschung*, 483.
- CORRENS, C. W. (1935), Die Verfahren der Gewinnung und Untersuchung der Sedimente. *Wiss. Ergeb. der deutschen atlant. Exp. Meteor Bd. III* Dritt teil. I Lief.
- CORRENS, C. W. (1937), Globigerinenschlamm, roter Ton und Blauschlick. *Naturwissenschaften*, 13.
- CRAMER, H. (1945), *Mathematical Methods of Statistics*. Princeton and Uppsala.
- EVANS, R. D. and KIP, ARTHUR (1938), The radium content of marine sediments from the East Indies, the Philippines and Japan and of the mesozoic fossil clays of the East Indies. *Amer. J. Sci.*, 36, 321.
- EVANS, R. D., KIP, A. F. and MOBERG, E. G. (1938), The radium and the radon content of Pacific Ocean water, life and sediment. *Amer. J. Sci. (5th Ser.)*, 36, 241-259.
- FOYN, E., KARLIK, B., PETTERSSON, H. and RONA, E. (1939), The radioactivity of sea water. *Medd. Oceanografiska Inst. Göteborg*, 2.
- HERNEGGER, F. and KARLIK, B. (1935), *Uranium in Seawater*. från Göteborgs högskolas oceanogr. inst., 12.
- HOLLAND, H. D. and KULP, J. L. (1954), The transport and deposition of uranium, ionium and radium in rivers, oceans and ocean sediments. *Geochim. et Cosmochim. Acta*, 5, 5, 197-213.
- HOLLAND, H. D. and KULP, J. L. (1954), The mechanism of removal of ionium and radium from the oceans. *Geochim. et Cosmochim. Acta*, 5, 5, 214-224.
- ISAAC, N. and PICCIOTTO, E. (1953), Ionium determination in deep-sea sediments. *Nature*, 171, 742.
- JOLY, J. (1908), On the radium content of deep-sea sediments. *Phil. Mag.*, 6, 190.
- KALLE, K. (1943), *Der Stoffhaushalt des Meeres*. Akad. Verlags Gesellschaft Leipzig.
- KOCZY, F. (1949), Thorium in sea water and marine sediments. *Geol. för i Stockholm förh.*, 11, 238.
- KOCZY, F. (1950), Zur Sedimentation und Geochemie im Aqueatorialen Atlantischen Ozean. *Medd. från Oceanografiska inst. Göteborg*, 17.
- KOCZY, F. (1951), Factors determining the element concentration in sediments. *Geochim. et Cosmochim. Acta*, 1, 2.
- KOCZY, F. (1954), Geochemical balance in the hydrosphere; in *Nuclear Geology*, ed. by H. FAUL, Wiley's.
- KOCZY, F. (1956), Radium in ocean water. *Rep. of the Swedish Deep-sea Exp.* (in preparation).
- KOCZY, F. and KRÖLL, V. (1956), The calculation of the rate of sedimentation from the Ra content in deep-sea sediments. *Rep. of the Swedish Deep-Sea Exp.* (in preparation).

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- KOCZY, G. (1950), Weitere Uranbestimmungen an Meerwasserproben. *Inst. für Radiumforschung*, 463.
- KRÖLL, V. (1955), On the distribution of radium in deep-sea sediments. *Rep. of the Swedish Deep-Sea Exp.*, vol. X.
- KRÖLL, V. (1954), On the age-determination in deep-sea sediments by radium measurements. *Deep-Sea Res.*, 1, 211-215.
- KUENEN, PH. H. (1950), *Marine Geology*, John Wileys & Sons, New York.
- NAKANISHI, M. (1951), Fluorometric microdetermination of uranium V. *Bull. Chem. Soc. Jap.*, 24, 36-38.
- PETTERSSON, H. (1930), Teneur en radium des depots de mer profonde. *Camp. Sci., Monaco*, 81.
- PETTERSSON, H. (1937), The proportion of thorium to uranium in rocks and in the sea. *Anz. Akad. Wiss. Wien, Math. Naturwiss. Klass* 127-128.
- PETTERSSON, H. (1943), Manganese nodules and the chronology of the ocean-floor. *Medd. Oceanogr. Inst. Göteborg*, 6.
- PETTERSSON, H. (1954), Radioactive elements in ocean waters and sediments. *Nuclear Geology*, ed. by H. FAUL, Wiley's.
- PICCIOTTO, E. and WILGAIN, S. (1954), Thorium determination in sediments. *Nature*, 173, 4405, 632.
- PIGGOT, C. S. (1933), Radium content of ocean bottom sediments. *Amer. J. Sci.*, 25, 229-238.
- PIGGOT, C. S. and URRY, W. D. (1942), Time relation in ocean sediments. *Bull. Geol. Soc. Amer.*, 53, 1187-1210.
- PIGGOT, C. S. and URRY, W. D. (1941), Radioactivity of ocean sediments: III. Radioactive relations in ocean water and bottom sediments. *Amer. J. Sci.*, 239, 81-91.
- RONA, E. and URRY, W. D. (1952), Radioactivity of ocean sediments: VIII. Radium and uranium content of ocean and river waters. *Amer. J. Sci.*, 250, 4, 241.
- RUBEY, W. (1951), Geologic history of sea water; an attempt to state the problem. *Bull. Geol. Amer. Soc.*, 62, 9, 1111-1148.
- SCHOTT, W. (1935), Die Foraminiferen in dem Äquatorialen Teil des atlantischen Ozeans. *Wiss. Ergeb. der deutschen atlant. Exp. Meteor. Bd. III Dritte Teil, I Lief.*
- SCHUBERT, J. (1949), in *Ion Exchange*, ed. by F. C. NACHOD; Application of ions exchange to the separation of inorganic cations, 167, Acad. Press Inc. Publ., N.Y.
- SMITH-GRIMALDIS (1953), in collected papers on Methods of Uranium and Thorium determination.
- URRY, W. D. (1950), Radioactivity of ocean sediments: VII. Rate of deposition of deep sea sediments. *J. Mar. Res.*, 7, 618-634.
- URRY, W. D. (1949), Radioactivity of ocean sediments: VI. Concentration of the radioactive elements in marine sediments of the southern hemisphere. *Amer. J. Sci.*, 247, 257-275.
- URRY, W. D. (1941), The radioactive determination of small amounts of uranium. *Amer. J. Sci.*, 239, 191-203.
- URRY, W. D. and PIGGOT, C. S. (1942), Radioactivity of ocean sediments: V. The concentration of the radioelements and their significance in red clay. *Amer. J. Sci.*, 240, 93-103.

Correlation of six cores from the equatorial Atlantic and the Caribbean

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Abstract—Curves of late Pleistocene climatic variation based on vertical distribution of planktonic Foraminifera in six cores from the Equatorial Atlantic and Caribbean have been satisfactorily correlated.

Variation in percentage of material coarser than 74 microns and variation in coiling direction of *Globorotalia truncatulinoides* have also been used in correlation.

Such correlation is construed as evidence that the sediment sections in these cores have accumulated slowly, and without interruption by slumping or turbidity current deposition.

INTRODUCTION

UNTIL fairly recently it was supposed that a core taken almost anywhere in deep water would contain an unbroken record of Pleistocene climatic changes. From study of hundreds of cores taken in the North Atlantic (Fig. 1) by Lamont Geological Observatory, Columbia University, it is now evident that slow uninterrupted particle by particle deposition in the deep oceans is the exception and not the rule. The interfering processes are, particularly, current scour, removal or emplacement of sediment by slumping and mud flow, and deposition by turbidity currents according to SHEPARD (1948), KUENEN (1950), ERICSON, *et al.* (1952). The six cores discussed in this paper were chosen for temperature determinations and radio-carbon dating because of good evidence that the contained sediment sections represent slow, uninterrupted particle by particle deposition. This evidence is briefly reviewed in the following paper.

In addition, curves of climatic variation based on vertical distribution of planktonic Foraminifera are presented.

THE CORE APPARATUS AND THE CONDITION OF THE CORES

Description of the Core Apparatus. The cores were obtained with a piston core apparatus which is mainly a modification of the apparatus designed by KULLENBERG (1947). A drawing of the apparatus is shown in Fig. 2.

The weight which supplies the force that drives the coring tube into the ocean bottom sediment is usually 1,000 to 2,000 lbs, and is made of lead. Instead of the lead discs as described in Fig. 2 the weight has lately been streamlined, and consists of one solid piece of lead as illustrated in Fig. 3. The weight is attached to the trawl wire by a trigger mechanism which has an arm that extends about 4 ft from the wire. A trigger-weight is attached to the arm by a cord. The length of the cord is chosen so that the trigger-weight hangs 10 to 15 ft below the lower end of the coring tube. The trigger-weight trips the release when it hits the ocean bottom, and allows the apparatus to fall freely into the sediment.

The standard coring tube is seamless steel tube obtained in nominal 20 ft lengths with $2\frac{1}{2}$ in. inside diameter and a wall thickness of $\frac{1}{8}$ in. When more than 60 ft of tubing is used the top section has a wall thickness of $\frac{3}{8}$ in. and the section next to the top section a wall thickness of $\frac{1}{2}$ in. The 20 ft tube lengths are coupled together and attached to the main weight by couplings which have a clearance of about .003 in. There are 18 holes in 3 rings of 6 for the screws at each connection. After the screws have been screwed in the couplings are wrapped with friction tape as an extra safety measure to stop water from entering the tube.

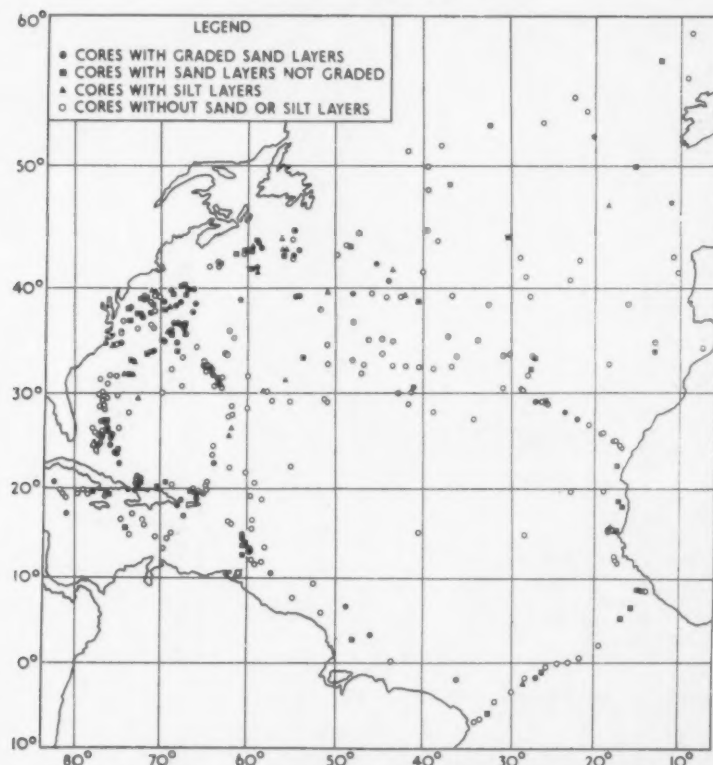


Fig. 1. Locations and distribution of the sediments in the majority of about 550 deep-sea cores which have been obtained from the Atlantic and the Caribbean. About 230 of the cores contain sand or silt layers. Many of the cores which on the chart are shown to contain graded sand layers also contain nongraded sand layers and silt layers; cores with non-graded sand layers also contain silt layers, and many of the silt layers are graded. The sand and silt layers are almost always found below a variable thickness of abyssal foraminiferal lutite or red clay. It is believed that the sand and silt have been transported and deposited by turbidity currents. Only about 15 of the cores without sand or silt layers consists completely of sediments that have been accumulated by normal process of deposition, that is, uninterrupted particle by particle deposition. In the other cores without sand and silt layers the sequence has been broken by slumping or mud flow.

The cutting edge is attached to the lower end of the coring tube by six screws similar to those used at the couplings. The core catcher consists of a piece of coring tube, $\frac{3}{8}$ in. long, and a piece of spring bronze which is spot-welded to the inside of the piece of coring tube. The piece of bronze is cut so that it has 15 equally spaced fingers which bend out against the wall of the tube when the core is entering.

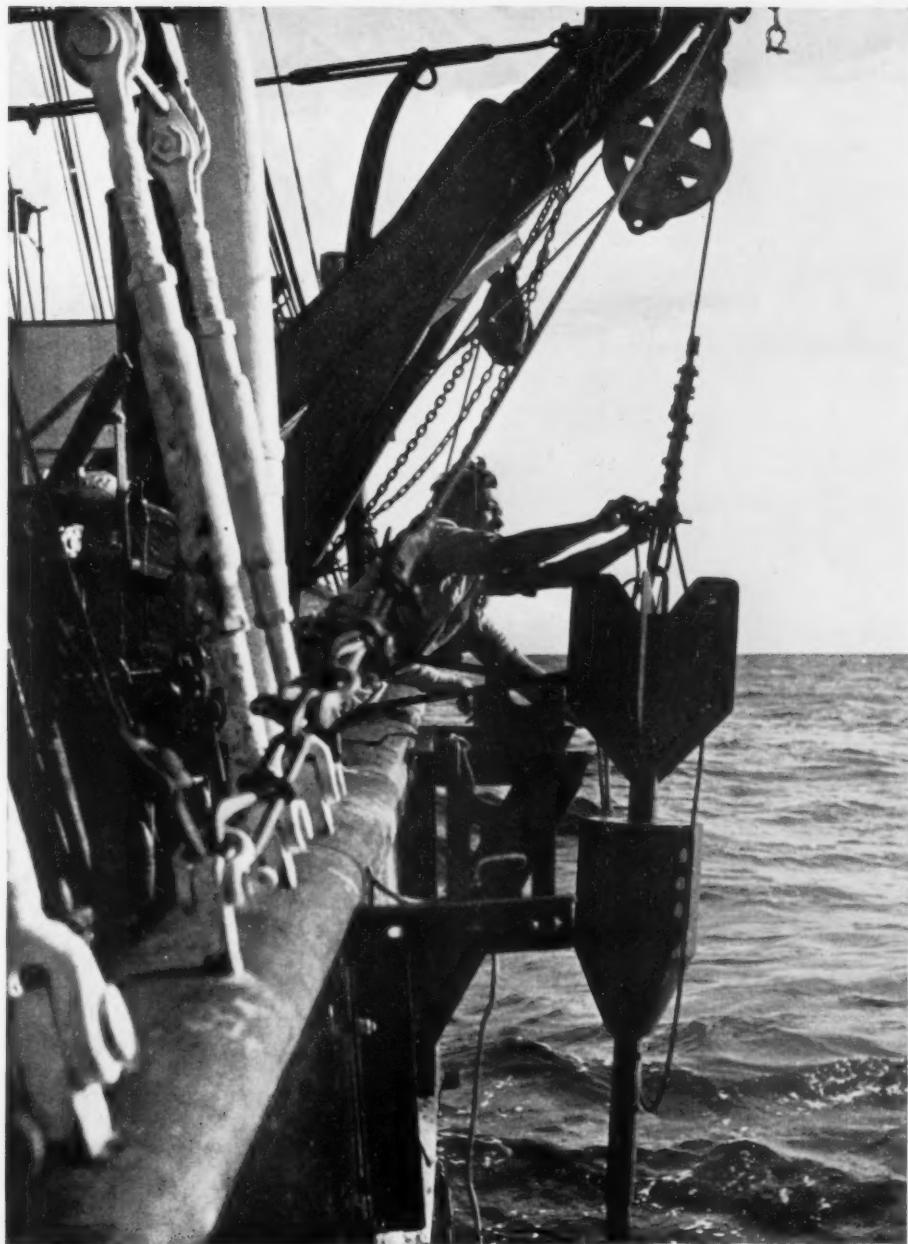


Fig. 3. The last operation before the piston core apparatus is lowered into the ocean: the safety pin is removed from the release mechanism. The main weight, below the tail-fin, is streamlined, cast of lead, and weighs 1,100 lb. The coring tube is assembled and taken apart while the apparatus is resting on supports which are attached to the hull.

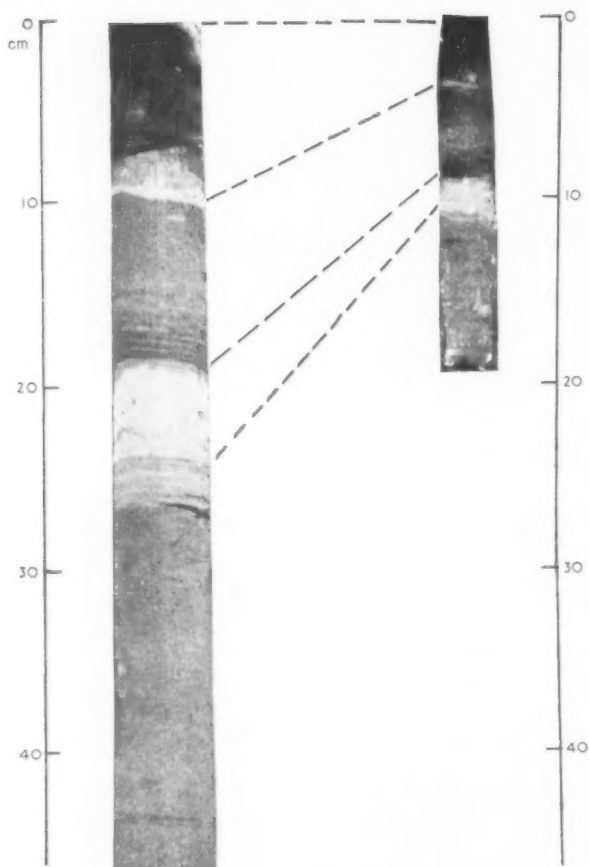


Fig. 4. To the left the top section of a piston core and to the right a trigger-weight core. The cores were obtained simultaneously at the same station. The split halves of the cores were cut out from the same photo, so the scale is the same. The difference in the width of the cores is due to the fact that the diameter, 6.3 cm, of the piston core is twice as big as that of the trigger-weight core. The piston core section is considered to be a correct representation of the sediment column *in situ*. Correlation of the sediment layers show that the trigger-weight core has been shortened about 50 per cent.

The shortening occurred because the core was taken with an apparatus without piston. The trigger-weight cores are obtained in order to be certain that the topmost sediments of the piston cores are present-day deposits. The tops of the trigger-weight cores are considered to represent present-day deposits because, taken short in plastic liners, they can be kept upright until sampled in the laboratory. Comparison of the core tops in the photo show that the piston core top is undisturbed.

If the core should start to slip out when the apparatus is hauled up, the core itself will force the fingers to bend in and prevent the core from slipping out of the tube.

A fiege fitting is attached to the outboard end of the trawl wire, and by its use a piston can be bolted to the end of the wire. The piston has three leather cups of the type used as piston rings in conventional water well pumps. The piston is placed at the bottom of the coring tube in contact with the catcher. The trawl wire from the piston extends through the coring tube, the axial tubular opening, the main weight, the release mechanism, the A-frame, to the winch. There is a constriction in diameter to 2 in. at a point near the bottom of the main weight, so that a bumper attached to the fiege fitting will not pass the constriction when the apparatus is hauled up. Because this constriction impedes the flow of water during rapid ascent of the piston in the pipe, there are ports just below it to permit some water to escape.

A clamp, known as a come-along, which is self-tightening, is used to attach the release mechanism to the trawl wire. The advantage of this device is that it can, after being hauled up and made fast to the A-frame, be loosened and thus allow the wire to pass through it while the main weight with the tube is hauled up. The come-along also makes it possible to hoist the main weight and tube into the cradle and supports, which are attached to the hull of the vessel, by means of a trawl winch; that is, without using auxiliary hoisting equipment.

The trigger weight is usually cast of lead, and ranges from 50 to 80 lb., depending upon the weight of the main weight. Attached to the bottom of the trigger-weight is a sampling tube, 1½ in. in diameter and about 1 ft long, with cutting edge, catcher, and a plastic liner.

The Core's Representation of the Sediment Column in situ. When a core is taken with an apparatus which has no piston, shortening occurs and the sediment column is not correctly represented by the core. The shortening of the core occurs because part of the sediment is squeezed aside as the friction between the sediment and the inner wall of the tube builds up. This problem has been studied and discussed by PRATJE (1934, 1939), EMERY and DIETZ (1941), PIGGOT (1941), and others.

To illustrate the shortening a photograph of the trigger-weight core and the top section of the piston core A179-5 (19°30'N, 76°26'W; 4,390 m) is shown in Fig. 4. The cores were obtained at the same time. The top section of the piston core and the trigger weight core are cut out from the same photograph so the scale is the same. It can clearly be seen that the core obtained by a corer without piston, the trigger-weight core, is shortened about 50 per cent. Core A179-5 was selected for the illustration because in this core the shortening is more obvious than in the cores which are described in this paper.

That a core which is obtained by a piston core apparatus is a correct representation of the sediment column *in situ* is discussed by KULLENBERG (1947). Good evidence, we believe, that the cores here described were not shortened by squeezing is provided by burrows of circular cross-section which can be found even at the bottom of the cores. There are also some unfilled burrows in the cores, but even these retain an undistorted cross-section. Therefore it is assumed that, when correlatable zones differ in thickness from core to core, it is because of a real difference in rate of accumulation, and not because of changes in the section due to the coring process.

The Tops of Piston Cores and Present-day Deposits. To be certain that the topmost layers of the piston cores are truly present-day deposits, trigger-weight cores are obtained at the same time. Because these cores are short, and taken in plastic liners which can be kept upright until sampled in the laboratory, the uppermost millimetre of sediment remains undisturbed and should be really representative of present-day deposits. Comparison of piston core tops with corresponding trigger-weight core tops shows that the piston cores have either undisturbed tops, or that only about 2 cm are missing at the tops of the piston cores. Other evidence for the relatively undisturbed tops of the cores are the following radiocarbon dates by SUESS: $3,700 \pm 200$ years for a sample taken between 0 and 10 cm from core A179-4; $2,960 \pm 200$ years for a sample taken between 0-8 cm from core A180-73.

LOCATIONS OF THE CORES AND TOPOGRAPHY

The locations of the cores are shown by Fig. 5. The geographical positions and depths of water are given in Table 1.

Table 1. Locations, depths and lengths of cores

Core	Latitude	Longitude	Depth in metres	Length in centimetres
A172-6	14°59'N	68°51'W	4160	935
A179-4	16°36'N	74°48'W	2965	690
A180-72	00°35.5'N	21°47'W	3840	472
A180-73	00°10'N	23°00'W	3750	490
A180-74	00°03'S	24°10'W	3330	480
A180-76	00°46'S	26°02'W	3510	425

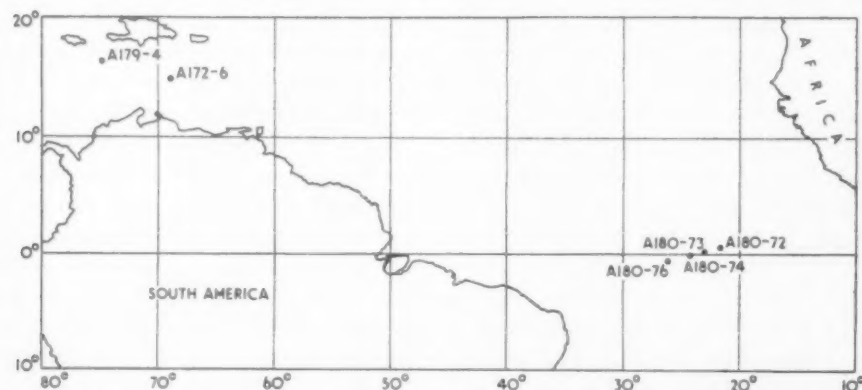


Fig. 5. Locations of the cores, which were selected from about 550 cores from the Atlantic and the Caribbean for the investigations reported in this paper. The cores were chosen because preliminary investigations showed that the cores contained an unbroken record of climatic and biological changes. The distance between core A180-72 and A179-4 is about 6,000 km, and between A180-72 and A180-76 about 480 km. The cores were raised from gently sloping areas.

A172-6 was taken on the crest of an eastern extension of the Beata Ridge.

A179-4 was taken on a gently sloping bottom southeast of the Albatross Bank to the east of Jamaica. The two stations are about 600 km apart and are separated by the Beata Ridge.

The four equatorial cores are about 6,000 km distant from A179-4. These latter were taken on the gently sloping flanks of the Mid-Atlantic Ridge, 72 and 73 on the NE slope, 74 near the crest, and 76 on the SW slope.

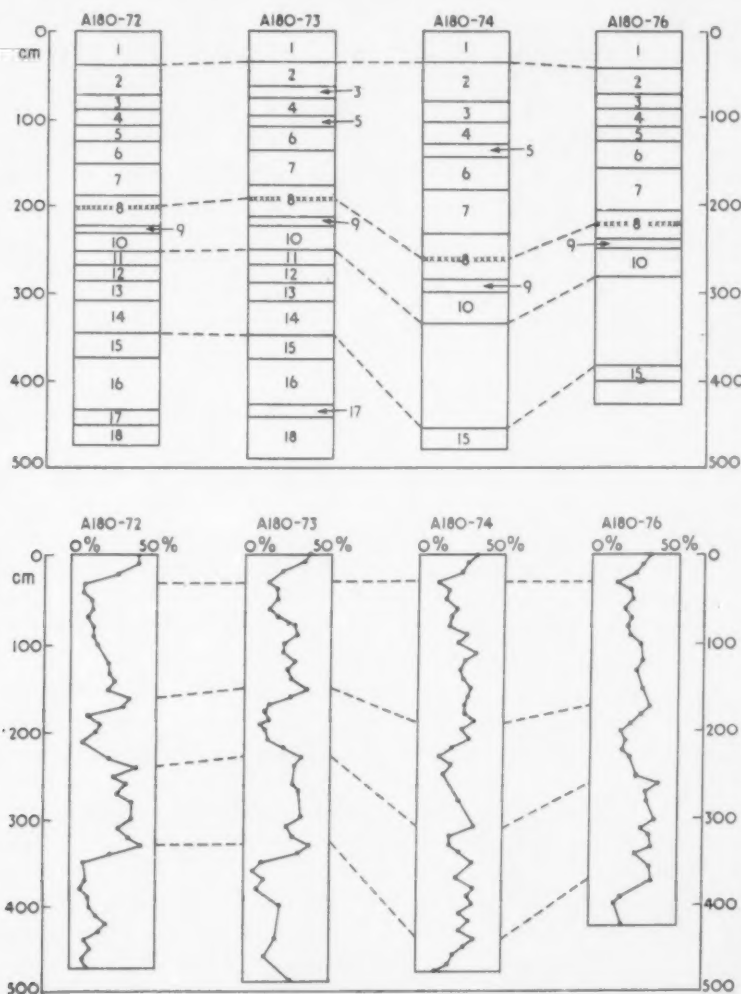


Fig. 6. Correlation by lithology and size-fraction analyses of the equatorial cores. The lines within each core in the top half of the drawing indicate boundaries where there are changes from dark-brown or dark-gray to light-brown or light-gray foraminiferal lutite. Corresponding numbers indicate correlating layers. Some numbers are missing in cores A180-74 and A180-76, because the layers are not clearly identified. The line of x's marks a thin layer which has an abundance of diatoms. The lower half of the drawing shows correlation of size fractions greater than 74 microns. The correlations also show that the rate of accumulation was about the same at stations A180-72 and A180-73, and that it was faster at A180-74 and A180-76.

LITHOLOGICAL DESCRIPTIONS

Core A172-6. The core consists of remarkably uniform brown foraminiferal lutite. Although there is some change in the shade of brown, there is nowhere in the core a section made up of cyclical gray layers, though it must include the time

interval represented by the gray layers. Presumably the brown terrigenous sediment in this core was derived from the South American continent. Apparently, Würm climate in this part of the world was not so different as to lead to any marked change in colour of the fine terrigenous sediment supplied by South American rivers to the Caribbean. It would seem, therefore, that the gray lutite of the equatorial areas must have had its origin either within the glaciated regions as rock flour or in the region peripheral to the continental glaciers. Probably there was some contribution from both sources.

Core A179-4. The core is brown foraminiferal lutite. As in the case of A172-6, though there are variations in shade of brown there are no cyclical gray layers. On the whole this core is very similar to A172-6 in lithology, and consequently needs no special comment.

Core A180-73. Essentially the core is made up of a series of layers of foraminiferal lutite of various shades of tan and gray.

From zero to 18 cm the colour is gray, gradually changing downward to tan which remains fairly uniform to 36 cm.

From 36 to 225 cm the colour is gray only.

From 225 to 376 cm the colour is dominantly tan, but with two layers having a total thickness of 40 cm; thus about $\frac{3}{4}$ of the section is tan.

From 376 to 490 cm the colour is dominantly gray, except for one tan layer only 14 cm thick.

Core A180-72, A180-74, and A180-76. These three cores of the equatorial suite are essentially similar in sequence of layers, differing principally in thicknesses of the individual layers as shown in Fig. 6. The only notable difference is that in the two westerly cores the layers numbered from 11 to 14 are so poorly defined that no attempt has been made to differentiate them.

The association of gray lutite with the zone of cold-water Foraminifera suggests that the source of terrigenous sediment was in some way influenced by the glacial climate. However, it is far from clear how the change in sediment colour was brought about.

A possible explanation may be that the glacial climate led to greater productivity of organic matter in this region, with consequent reduction of iron in the accumulating sediments.

Another puzzling characteristic of the cold-water section is its "cyclical" layering. It is made up of nine distinct layers, each distinguished by abrupt change from light gray to dark gray at the base, with gradual change upward into dark gray lutite again. The boundaries of each layer are well defined except to the extent that they are somewhat blurred by burrowing animals. Again, rather sudden minor climatic changes within the Würm glacial stage might conceivably have led to marked changes in organic productivity, and consequently to more or less pigmentation or reduction of the resulting sediments. However, until more is known about the chemical and organic content of these peculiar layers it is hardly profitable to speculate on their origin.

SIZE FRACTIONS GREATER THAN 74 MICRONS

Samples for paleontological examination are prepared by washing the sample on a 200-mesh sieve having 74 micron spaces between wires.

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It has for some times been routine practice to weigh the original sample and the coarse material retained on the sieve from which the percentage of coarse material is then taken. In these cores taken at stations where the bottom has not been subject to bottom scour, or deposition by turbidity currents, the tests of foraminifera and the smallest terrigenous particles settled essentially vertically downwards, and having reached the bottom remained undisturbed. Since coarse mineral particles and shells of benthic Foraminifera occur in negligible amounts in these deep-sea sediments, and

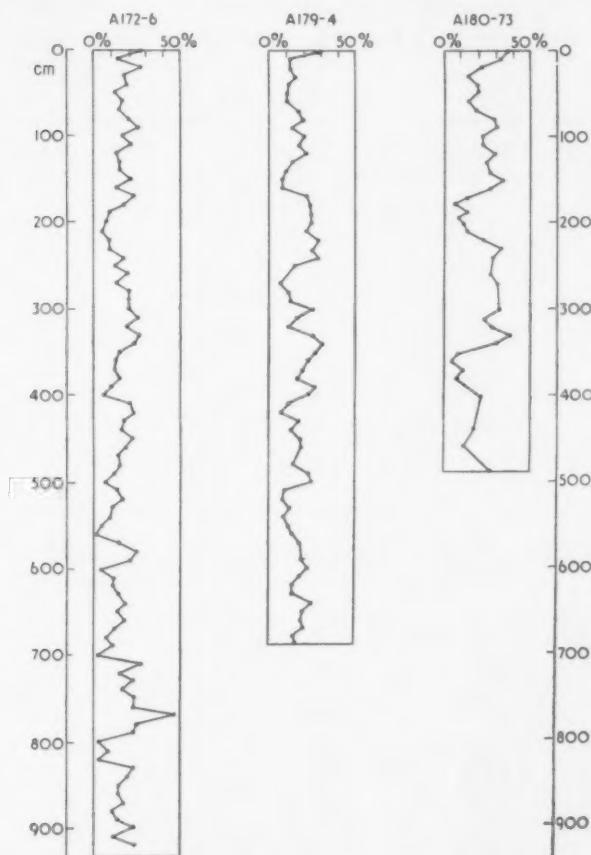


Fig. 7. Comparison of the size fraction analyses of the Caribbean cores, A172-6 and A179-4, and a core from the equatorial Atlantic. The curves indicate percentage of size fraction greater than 74 microns. Correlation between A180-73 and A179-4 is evident.

since essentially all of the tests of planktonic Foraminifera are larger than 74 micron diameter, it is evident that the percentage of material coarser than 74 microns in any sample is a rough measure of the productivity of planktonic Foraminifera at the time of deposition. In the long run this productivity should be related to large scale climatic variations. Such climatic changes would probably affect large areas of the North Atlantic simultaneously. A masking effect should result from variations

in productivity of the Coccolithoforidae, particularly if their productivity increases concurrently with that of the Foraminifera. However, curves of variation in percentage of the seventy-four micron size fraction in the four equatorial cores show that masking effect of fine organically precipitated calcium carbonate has not destroyed the usefulness of this simple method. The results of the size-fraction analyses are shown in Figs. 6 and 7.

CHEMICAL ANALYSES

The results of carbonate analyses of samples from two of the cores are shown in Table 2. The alkalimeter method was used. This gives a direct measure of the weight

Table 2. Calcium carbonate analyses

Core A179-4		Core A180-73	
Sample position in cm from top	% CaCO ₃	Sample position in cm from top	% CaCO ₃
Top	77.0	Top	66.1
21	67.0	61	58.0
35	50.7	91	76.0
152	43.7	98	68.0
262	49.6	177	53.0
390	53.6	192	61.0
440	48.8	291	62.0
490	63.3	336	73.5
540	46.4		
590	61.4		
640	59.7		
690	55.0		

Table 3. Spectrochemical analyses of top samples

	A172-6 %	A179-4 %
SiO ₂	19.0	17.0
Al ₂ O ₃	11.0	9.0
TiO ₂	0.32	0.28
Fe ₂ O ₃	3.3	3.1
MgO	3.0	3.4
CaO	36.0	37.0
Na ₂ O	3.0	2.5
K ₂ O	1.5	1.1
SrO	0.092	0.12
MnO	0.15	0.18
CuO	0.004	0.008
V ₂ O ₅	0.020	0.018
BaO	0.022	0.024
Cr ₂ O ₃	0.018	0.018
B ₂ O ₃	0.07	0.06
PbO	0.008	0.008

of carbon dioxide lost by treatment of the sediment with hydrochloric acid. In order to make our values roughly comparable with other published data, we have assumed the carbon dioxide to have been present in the sediment as calcium carbonate. Thus the values given are percentages by weight of "calcium carbonate" in dry

Table 4. Distribution of planktonic foraminifera in Core A172-6

Sample position in cm from top	<i>G. m. men.</i>	<i>G. m. tum.</i>	<i>G. m. flex.</i>	<i>G. p. hirs.</i>	<i>G. p. punct.</i>	<i>G. t. R.</i>	<i>G. t. L.</i>	<i>G. scit.</i>	<i>G. infl.</i>	<i>G. bull.</i>	<i>G. pach.</i>	<i>G. egg.</i>	<i>G. rub.</i>	<i>G. sac.</i>	<i>G. cong.</i>	<i>O. uni.</i>	<i>Pul. obl.</i>	<i>Sph. deh.</i>
Top	A	C	X	X	X	1	1	R	X	X	X	C	A	A	F	A	C	C
10	V	A	X	R	R	18	5	A	X	X	R	V	V	V	C	A	R	R
20	A	C	X	R	R	98	8	A	R	X	R	V	V	V	C	A	R	R
30	X	A	X	X	X	156	15	A	R	X	R	V	V	V	C	A	R	R
40	X	C	X	X	X	100	17	A	R	X	R	V	V	V	C	A	R	R
50	R	R	X	X	X	82	2	A	A	X	X	V	V	V	C	A	R	R
60	X	X	X	X	X	69	1	A	R	X	X	V	V	V	C	A	R	R
70	X	X	X	X	X	66	4	C	R	X	X	V	V	V	C	A	R	R
80	X	X	X	X	X	72	1	A	V	X	X	V	V	V	C	A	R	R
90	X	X	X	X	X	100	25	A	V	X	X	V	V	V	C	A	R	R
100	X	X	X	X	X	100	10	A	V	X	X	V	V	V	C	A	R	R
110	X	X	X	X	X	100	26	A	V	X	X	V	V	V	C	A	R	R
120	X	X	X	X	X	100	7	C	F	X	R	V	V	V	C	A	R	R
130	X	X	X	X	X	100	13	V	F	X	R	V	V	V	C	A	R	R
140	X	X	X	X	X	69	11	C	F	X	R	V	V	V	C	A	R	R
150	V	F	V	V	V	97	10	C	F	X	R	V	V	V	C	A	R	R
160	V	R	V	V	V	95	3	V	F	R	R	V	V	V	C	A	R	R
170	V	R	V	V	V	58	1	V	V	R	R	V	V	V	C	A	R	R
180	X	X	X	X	X	90	4	V	V	X	R	V	V	V	C	A	R	R
190	X	X	X	X	X	61	1	C	A	R	F	V	V	V	C	A	R	R
200	X	X	X	X	X	100	1	A	A	X	F	V	V	V	C	A	R	R
210	X	C	X	X	X	100	1	V	X	R	C	V	V	V	C	A	R	R
220	X	C	C	X	X	100	1	V	X	R	C	V	V	V	C	A	R	R
230	X	V	C	X	X	100	2	V	X	R	C	V	V	V	C	A	R	R
240	X	V	V	X	X	100	2	V	X	R	C	V	V	V	C	A	R	R
250	X	V	V	X	X	100	1	V	X	R	C	V	V	V	C	A	R	R
260	X	V	V	X	X	100	1	V	X	R	C	V	V	V	C	A	R	R
270	X	V	V	X	X	100	9	V	X	R	C	V	V	V	C	A	R	R
280	X	V	V	X	X	100	1	V	X	R	C	V	V	V	C	A	R	R
290	X	V	V	X	X	100	2	X	X	X	X	V	V	V	C	A	R	R
300	90% broken																	
310	X	V	V	X	X	100	5	F	X	X	X	X	V	V	V	V	F	X
320	X	V	V	X	X	100	3	F	C	X	X	C	V	V	V	V	V	F
330	X	V	V	X	X	100	2	F	F	X	X	V	V	V	V	V	V	F
340	F	V	V	R	F	100	3	F	F	X	X	V	V	V	V	V	V	F
350	X	V	X	C	C	100	3	V	V	X	X	V	V	V	V	V	V	F
360	X	V	X	C	C	100	4	V	V	X	X	V	V	V	V	V	V	F
370	X	V	X	X	X	100	0	V	V	X	X	V	V	V	V	V	V	F
380	X	V	C	X	X	100	4	V	V	X	X	V	V	V	V	V	V	F
390	X	V	C	X	X	100	1	V	V	X	X	V	V	V	V	V	V	F
400	X	V	C	X	X	82	3	V	V	X	X	V	V	V	V	V	V	F
410	X	V	C	X	X	100	1	V	V	X	X	V	V	V	V	V	V	F
420	X	V	C	X	X	100	4	V	V	X	X	V	V	V	V	V	V	F
430	X	V	C	X	X	100	3	F	X	R	R	V	V	V	V	V	V	F
440	F	V	C	X	X	100	8	X	X	R	R	V	V	V	V	V	V	F
450	A	V	R	X	R	100	2	X	C	X	X	V	V	V	V	V	V	F
460	V	V	A	X	X	100	3	C	A	X	X	V	V	V	V	V	V	F
470	A	V	A	X	X	100	9	F	V	X	C	A	V	V	V	V	V	F
480	V	V	V	X	X	100	8	V	V	X	A	A	V	V	V	V	V	F
490	V	X	C	X	X	100	4	V	V	X	A	A	V	V	V	V	V	F
500	V	X	X	X	X	100	6	V	V	X	A	A	V	V	V	V	V	F
510	V	X	A	X	X	100	4	V	V	X	R	A	V	V	V	V	V	F
520	V	V	V	X	X	100	3	R	R	X	R	A	V	V	V	V	V	F
530	F	V	V	X	X	100	7	R	R	X	R	A	V	V	V	V	V	F
540	X	V	V	R	C	100	8	X	R	X	R	A	V	V	V	V	V	F
560	70% broken																	
570	80% broken																	
580	R	A	V	X	V	2	2	R	R	X	R	A	V	V	V	C	A	A
590	A	V	A	X	V	32	26	R	V	X	A	A	V	V	V	V	A	R
600	A	V	A	X	C	12	25	V	A	X	A	A	V	V	V	V	A	R

Table 4 (cont.). Distribution of planktonic foraminifera in Core A172-6

Sample position in cm from top	G. m. men.	G. m. tum.	G. m. flex.	G. p. hirs.	G. p. punct.	G. trc. R.	G. trc. L.	G. scit.	G. infl.	G. bull.	G. pach.	G. egg.	G. rub.	G. sac.	G. cong.	O. uni.	Pul. obl.	Sph. deh.
610	V	V	A	X	R	100	5	V	A	X	A	A	V	V	A	V	X	X
620	V	A	X	X	X	73	108	V	V	X	A	A	V	V	V	V	X	X
630	V	A	X	X	X	100	5	V	X	X	A	A	V	V	V	V	X	X
640	V	A	X	X	X	100	5	V	X	R	X	A	V	V	V	V	X	X
650	V	A	X	X	X	100	2	V	X	X	A	A	V	V	V	V	X	X
660	V	A	X	X	A	100	1	V	X	X	A	A	V	V	V	V	X	X
670	V	A	X	X	A	100	4	V	C	X	A	A	V	V	V	A	X	F
680	80% broken																	
690	80% broken																	
700	85% broken																	
710	R	X	X	F	A	43	3	R	V	X	A	A	V	V	F	V	V	A
720	X	X	X	F	V	38	5	R	V	X	X	A	V	V	A	V	V	A
730	X	X	X	X	V	22	15	V	V	X	X	A	V	V	C	V	V	C
740	X	X	X	X	A	7	34	V	V	X	X	A	V	V	C	V	V	F
750	X	X	X	X	A	4	57	V	V	X	X	X	V	V	C	V	V	F
760	X	X	X	X	A	26	50	V	F	X	X	X	V	V	A	V	V	F
770	X	X	X	X	A	19	65	V	V	X	X	X	V	V	A	V	V	C
780	X	X	X	X	A	53	46	V	V	X	X	X	V	V	A	V	V	C
790	R	X	X	X	A	100	10	V	A	X	X	X	V	V	A	V	V	C
800	90% broken																	
810	60% broken																	
820	70% broken																	
830	X	X	X	X	C	68	14	R	A	X	X	A	V	V	V	V	V	V
840	X	X	X	X	A	36	47	X	R	X	X	A	V	V	V	V	V	A
850	X	X	X	X	A	50	31	R	X	X	X	A	V	V	V	V	V	A
860	X	X	X	X	A	6	25	C	X	X	X	A	V	V	V	V	V	A
870	X	X	X	X	A	54	5	V	X	X	X	A	V	V	V	V	V	A
880	A	X	X	X	A	105	2	V	X	A	X	A	V	V	V	V	X	X
890	V	X	X	X	A	100	2	V	A	X	A	A	V	V	V	V	X	X
900	V	X	X	X	C	100	4	V	C	R	X	A	V	V	V	V	X	R
910	V	X	X	X	C	25	1	V	A	X	C	C	V	V	A	V	V	F
920	V	X	X	X	F	100	2	V	V	X	A	C	V	V	F	V	X	F
935	80% broken																	

unwashed sediment. From the nature of the analyses any magnesium carbonate will be included in the "calcium carbonate," however, the error in total carbonate from this source is probably somewhat less than that inherent in the alkalimeter method itself, in which the error is in the order of one or two per cent. The point to be emphasized is that the values given are approximate measures of total carbonate present, and not percentages of calcium carbonate alone. Admittedly the method is crude. However, since the variation in carbonate content from sample to sample is so much greater than any error due to the method, we feel that the data are of sufficient significance to be published.

The results of spectrochemical analyses of the top samples from Core A172-6 and A179-4 are shown in Table 3. The analyses were made by Dr. R. G. SMALLEY of California Research Corporation.

MICROPALAEONTOLOGICAL ANALYSIS

In this laboratory it is customary to take samples about 1 cm thick at intervals of approximately 10 cm. The weights of such samples vary about an average of 5 gm. After drying and weighing, the samples are washed on a sieve. It has been

Table 5. Distribution of planktonic foraminifera in Core A179-4

Sample position in cm from top	<i>G. m. men.</i>	<i>G. m. tum.</i>	<i>G. m. flex.</i>	<i>G. p. hirs.</i>	<i>G. p. punct.</i>	<i>G. trc. R.</i>	<i>G. trc. L.</i>	<i>G. scit.</i>	<i>G. infl.</i>	<i>G. bull.</i>	<i>G. pach.</i>	<i>G. egg.</i>	<i>G. rub.</i>	<i>G. sac.</i>	<i>G. cong.</i>	<i>O. uni.</i>	<i>Pul. obl.</i>	<i>Sph. deh.</i>
Top	V	A	X	X	F	58	21	C	X	X	X	V	V	V	F	A	C	C
10	V	A	X	X	F	11	5	C	X	X	X	V	V	V	F	A	C	C
20	V	A	X	X	F	68	11	C	X	X	X	V	V	V	F	A	C	C
30	X	R	X	X	C	73	3	A	V	F	X	V	V	V	C	V	X	V
40	R	X	X	X	C	100	1	V	V	X	X	V	V	V	A	V	X	X
50	R	X	X	X	C	100	2	A	V	X	X	V	V	V	A	V	X	X
60	X	X	X	X	A	100	4	V	V	R	X	V	V	V	A	V	X	X
70	X	X	X	X	A	100	22	V	V	R	X	V	V	V	A	V	X	X
80	X	X	X	X	C	100	14	V	V	R	R	V	V	V	A	V	X	X
90	R	X	X	X	A	95	31	V	V	R	R	V	V	V	A	V	X	X
100	R	X	X	X	A	84	40	V	V	R	R	V	V	V	A	V	X	X
110	F	X	X	X	A	100	7	A	V	R	R	V	V	V	A	V	X	X
120	X	X	X	X	A	100	2	V	V	R	R	V	V	V	A	V	X	X
130	R	X	X	X	A	100	2	V	V	A	C	V	V	V	A	V	X	X
140	R	X	X	X	C	100	8	V	V	R	R	V	V	V	A	V	X	X
150	R	X	X	X	A	97	7	V	V	R	R	V	V	V	A	V	X	X
160	R	X	X	X	R	100	39	A	C	C	X	V	V	V	A	V	X	X
170	C	X	R	A	A	35	60	V	X	X	X	V	V	V	A	V	X	X
180	V	X	A	X	V	51	17	V	X	X	X	V	V	V	A	V	X	X
190	V	V	X	A	V	100	17	V	C	C	X	V	V	V	A	V	X	X
200	V	V	V	V	X	27	4	V	X	C	X	V	V	V	A	V	X	X
210	V	A	V	V	X	100	10	A	X	R	X	V	V	V	A	V	X	X
220	A	C	V	V	V	100	6	V	X	C	X	V	V	V	A	V	X	X
230	V	A	C	V	V	14	4	V	X	C	X	V	V	V	A	V	X	X
240	V	V	X	V	V	18	3	A	C	C	X	V	V	V	A	V	X	X
250	V	V	X	X	C	100	11	V	V	X	X	V	V	V	A	V	X	X
260	V	X	X	X	A	100	2	V	V	V	X	V	V	V	A	V	X	X
265	R	X	X	X	V	100	20	V	V	V	V	V	V	V	A	V	X	X
270	F	R	C	X	C	100	4	V	V	V	C	V	V	V	A	V	X	X
275	R	C	X	X	A	100	4	V	V	V	C	V	V	V	A	V	X	X
280	V	A	A	R	C	100	1	V	A	X	X	V	V	V	A	V	X	X
290	A	A	V	X	C	100	6	A	A	X	C	V	V	V	A	V	X	X
300	V	V	A	X	A	100	3	V	X	R	C	V	V	V	A	V	X	X
310	A	V	V	X	A	100	2	V	X	X	C	V	V	V	A	V	X	X
320	A	V	V	X	A	100	2	V	X	X	C	V	V	V	A	V	X	X
330	A	V	V	X	F	100	18	A	X	X	C	V	V	V	A	V	X	X
340	A	V	V	X	C	100	8	A	X	X	X	V	V	V	A	V	X	X
350	A	V	V	X	C	100	6	V	X	X	X	V	V	V	A	V	X	X
360	V	V	V	X	C	100	3	V	X	X	X	V	V	V	A	V	X	X
370	V	V	V	X	R	100	2	V	X	X	X	V	V	V	A	V	X	X
380	A	V	V	R	F	100	2	A	X	R	A	V	V	V	A	V	X	X
390	A	V	V	R	C	100	3	V	V	C	F	V	V	V	A	V	X	X
400	V	R	X	X	C	100	0	V	V	C	F	V	V	V	A	V	X	X
410	V	V	A	X	C	59	2	V	V	C	F	V	V	V	A	V	X	X
420	V	V	V	X	A	100	2	V	V	C	F	V	V	V	A	V	X	X
430	V	V	V	X	R	100	1	V	V	C	F	V	V	V	A	V	X	X
440	V	C	X	X	C	100	11	V	V	X	F	V	V	V	A	V	X	X
450	V	C	X	X	R	100	0	V	A	X	C	V	V	V	A	V	X	X
460	V	A	V	X	C	100	5	V	X	X	X	V	V	V	A	V	X	X
470	V	A	V	X	R	100	14	V	X	X	X	V	V	V	A	V	X	X
480	V	A	V	X	C	80	6	C	X	X	X	V	V	V	A	V	X	X
490	V	V	V	X	A	5	2	A	X	R	X	V	V	V	A	V	X	X
500	V	V	V	X	A	4	1	V	X	R	X	V	V	V	A	V	X	X
510	V	V	F	X	R	66	84	V	R	X	X	V	V	V	A	V	X	X
520	V	F	F	X	R	83	43	V	R	X	F	V	V	V	A	V	X	X
530	V	F	F	X	R	100	7	V	X	X	C	V	V	V	A	V	X	X
540	V	F	F	X	R	100	5	V	X	X	C	V	V	V	A	V	X	X
550	V	X	X	X	F	100	5	V	X	X	C	V	V	V	A	V	X	X
560	V	X	X	X	A	49	7	V	X	X	C	V	V	V	A	V	X	X
570	V	F	X	R	A	100	4	V	X	X	C	V	V	V	A	V	X	X

Table 5 (cont.). Distribution of planktonic foraminifera in Core A179-4

Sample position in cm from top	<i>G. m. men.</i>	<i>G. m. tum.</i>	<i>G. m. flex.</i>	<i>G. p. hirs.</i>	<i>G. p. punct.</i>	<i>G. trc. R.</i>	<i>G. trc. L.</i>	<i>G. scit.</i>	<i>G. infl.</i>	<i>G. bull.</i>	<i>G. pach.</i>	<i>G. egg.</i>	<i>G. rub.</i>	<i>G. sac.</i>	<i>G. cong.</i>	<i>O. uni.</i>	<i>Pul. obl.</i>	<i>Sph. deh.</i>
580	C	R	X	R	A	29	2	V	X	F	R	A	V	V	V	V	A	V
590	R	X	X	R	A	69	5	V	A	F	A	A	V	V	V	V	A	V
600	R	X	X	R	V	70	2	V	V	X	A	A	V	V	V	V	V	V
610	A	X	X	X	A	100	31	V	A	C	F	A	V	V	F	V	V	C
620	C	X	X	X	A	34	30	V	A	F	R	A	V	V	V	V	A	R
630	A	X	F	X	A	92	45	A	V	F	A	V	V	V	V	V	A	F
640	C	X	X	X	A	69	8	V	F	X	F	A	V	V	V	V	V	V
650	C	C	C	X	A	25	17	V	X	X	A	A	V	V	V	V	A	A
660	A	C	R	X	A	54	10	V	R	X	A	A	V	V	C	V	V	A
670	A	C	C	X	A	100	12	V	X	X	A	V	V	V	C	V	V	A
680	F	X	X	X	A	53	31	V	X	X	A	V	V	V	V	V	V	A
690	C	X	X	X	A	100	48	V	F	X	A	A	V	V	A	V	A	A

found that a 200 mesh (74 micron openings) sieve is most satisfactory for this purpose.

As a rule samples of this size yield at least enough material to cover a tray of 50 cm² area.

The tray having been covered, the species of planktonic Foraminifera are noted and the abundance of each is indicated on the faunal chart by one of the following symbols. (These symbols are also used in Tables 4, 5 and 6.)

X	Absent	
R	Rare	1-5 specimens per tray
F	Frequent	6-10
C	Common	11-25
A	Abundant	26-100
V	Very abundant	more than 100

At the same time right and left coiling shells of *Globorotalia truncatulinoides* are counted. If the species is very abundant, the count is continued until 100 shells of one or the other coiling direction have been counted. This has been found to give the ratio with sufficient accuracy without too great expenditure of time. (In Tables 4, 5 and 6 there are columns for the count of right- and left-coiling shells of *Globorotalia truncatulinoides*.) Normally benthic species of Foraminifera make up less than one per cent of the material on the tray. Thus change in abundance of a planktonic species is normally not due to dilution of the sample by mineral particles or benthic species. It is due rather to a change in the proportion of individuals of the particular species in the total population of planktonic Foraminifera.

Admittedly this method of analysis is crude, but it has the great merit of rapidity, and this has made it possible to examine suites of samples from hundreds of cores taken in the North Atlantic. The resulting abundance of data has, we feel, given a statistical validity to our findings which could not otherwise have been obtained.

Table 6. Distribution of planktonic foraminifera in Core A180-73

Sample position in cm from top	<i>G. m. men.</i>	<i>G. m. tum.</i>	<i>G. m. flex.</i>	<i>G. p. hirs.</i>	<i>G. p. punct.</i>	<i>G. trc. R.</i>	<i>G. trc. L.</i>	<i>G. scit.</i>	<i>G. infl.</i>	<i>G. bull.</i>	<i>G. pach.</i>	<i>G. egg.</i>	<i>G. rub.</i>	<i>G. sac.</i>	<i>G. cong.</i>	<i>O. uni.</i>	<i>Pul. obl.</i>	<i>Sph. deh.</i>
Top	V	A	X	X	C	21	0	A	X	X	X	C	V	V	X	R	V	R
10	V	V	X	R	C	47	0	A	X	X	X	A	V	V	X	A	V	C
20	R	R	X	R	V	101	2	A	V	X	X	A	V	V	X	A	V	X
30	X	R	X	X	V	100	3	F	X	X	X	V	V	V	X	X	X	X
40	X	R	X	X	V	100	3	F	X	X	X	V	V	V	X	X	X	X
50	X	X	X	X	V	100	1	F	V	V	A	V	V	V	X	R	X	X
60	X	X	X	X	V	100	6	R	V	A	V	V	V	V	X	R	X	X
70	X	X	X	X	V	100	5	R	V	A	V	V	V	V	X	R	X	X
80	X	X	X	X	A	100	4	R	V	V	V	V	V	V	X	R	X	X
90	X	X	X	X	V	100	3	R	V	V	V	V	V	V	X	R	X	X
100	X	X	X	R	A	100	3	R	V	V	R	V	V	V	X	R	X	X
110	X	X	X	X	A	100	3	R	V	V	A	V	V	V	X	R	X	X
120	X	X	X	X	A	100	3	R	V	V	A	V	V	V	X	R	X	X
130	X	X	X	X	A	100	1	A	A	A	A	V	V	V	X	R	X	X
140	X	X	X	X	A	100	2	F	A	A	A	V	V	V	X	R	X	X
150	X	X	X	X	A	100	2	F	A	A	A	V	V	V	X	R	X	X
160	X	X	X	X	A	100	2	F	C	X	A	V	V	V	X	R	X	X
170	X	X	X	X	A	100	7	C	F	A	A	V	V	V	X	R	X	X
177	X	X	X	X	A	100	1	R	C	C	V	V	V	V	X	R	X	X
193	X	X	X	X	V	100	4	X	R	X	V	V	V	V	X	R	X	X
200	X	X	X	X	C	100	45	R	C	F	X	V	V	V	X	R	X	X
210	R	X	X	X	C	54	100	C	C	X	R	V	V	V	X	R	X	X
220	F	X	R	R	V	100	8	C	A	X	X	V	V	V	X	R	X	X
230	A	F	F	X	V	100	2	C	A	X	X	V	V	V	X	R	X	X
240	V	V	V	X	V	100	5	V	F	X	R	V	V	V	X	R	X	X
250	V	V	V	X	A	100	4	X	C	X	R	V	V	V	X	R	X	X
260	V	V	V	R	C	140	3	R	A	X	X	V	V	V	X	R	X	X
270	V	V	V	X	F	130	3	F	A	X	X	V	V	V	X	R	X	X
280	A	V	V	X	A	100	4	C	A	X	R	V	V	V	X	R	X	X
290	A	V	V	X	A	100	2	R	A	R	R	V	V	V	X	R	X	X
300	A	V	V	F	C	100	5	X	X	X	X	V	V	V	X	R	X	X
310	V	V	V	R	C	100	6	X	X	X	X	V	V	V	X	R	X	X
320	V	V	V	X	C	100	6	X	X	X	X	V	V	V	X	R	X	X
330	V	V	V	X	C	100	12	R	R	X	X	V	V	V	X	R	X	X
335	V	V	V	X	V	46	100	C	R	R	X	V	V	V	X	R	X	X
340	V	F	F	X	V	44	17	C	C	R	X	V	V	V	X	R	X	X
350	V	F	X	X	A	76	3	F	R	R	X	V	V	V	X	R	X	X
360	A	X	X	X	A	100	3	R	R	A	V	V	V	V	X	R	X	X
370	C	X	R	X	A	100	2	R	R	V	V	V	V	V	X	R	X	X
380	X	X	X	X	A	100	3	R	C	V	V	V	V	V	X	R	X	X
400	R	X	X	F	V	100	2	R	R	V	V	V	V	V	X	R	X	X
440	A	X	X	X	V	100	3	R	V	C	X	V	V	V	X	R	X	X
460	V	X	F	X	C	36	2	C	V	X	V	V	V	V	X	R	X	X
490	V	V	V	R	A	59	3	F	A	R	R	V	V	V	X	R	X	X

The following list includes the species of planktonic Foraminifera which have been noted:

Globorotalia menardii menardii (d'Orbigny)
Globorotalia menardii tumida (H. B. Brady)
Globorotalia menardii flexuosa (Koch)
Globorotalia punctulata hirsuta (d'Orbigny)
Globorotalia punctulata punctulata (d'Orbigny)
Globorotalia truncatulinoidea (d'Orbigny)

Abbreviations used in Tables

G. m. men.
G. m. tum.
G. m. flex.
G. p. hirs.
G. p. punct.
G. trc. (R and L indicate Right and Left coiling shells)

<i>Globorotalia scitula</i> (H. B. Brady)	
<i>Globigerina inflata</i> d'Orbigny	<i>G. infl.</i>
<i>Globigerina bulloides</i> d'Orbigny	<i>G. bull.</i>
<i>Globigerina pachyderma</i> (Ehrenberg)	<i>G. pach.</i>
<i>Globigerina eggeri</i> (Rhumbler)	<i>G. egg.</i>
<i>Globigerinoides ruber</i> (d'Orbigny)	<i>G. rub.</i>
<i>Globigerinoides sacculifer</i> (H. B. Brady)	<i>G. sac.</i>
<i>Globigerinoides conglobatus</i> (H. B. Brady)	<i>G. cong.</i>
<i>Orbulina universa</i> d'Orbigny	<i>O. uni.</i>
<i>Pulleniatina obliquiloculata</i> (Parker and Jones)	<i>Pul. obl.</i>
<i>Sphaeroidinella dehiscens</i> (Parker and Jones)	<i>Sph. deh.</i>

These species have been excellently figured and discussed in papers by CUSHMAN and HENBEST (1940), and by PHLEGER, PARKER and PIERSON (1953). Some modification of the usual classification has seemed admissible in dealing with variation in *G. menardii*, (*s.l.*) and *G. punctulata*, (*s.l.*)

We have found that in some samples and at some stations there is intergradation between *G. menardii* (*s.s.*) and *G. tumida* (Brady). Thus the interrelationship is below the species level. Evidently H. B. BRADY appreciated this, for he described *G. tumida* as *Pulvinulina menardii* var. *tumida*. Since *G. menardii* has priority we are making *G. m. menardii* the nominate subspecies, and are reducing *G. tumida* to the rank of subspecies, as *G. menardii tumida*.

G. m. flexuosa was first described by KOCH (1923) from the late Cenozoic of Java as *Pulvinulina tumida* var. *flexuosa*. It occurs in abundance below the zone of cool climate deposition, frequently in association with *G. m. menardii*. We are making KOCH's variety a sub-species of *G. menardii* because, as with *G. m. tumida*, there is complete intergradation between it and *G. m. menardii*. Apparently this subspecies is extinct in the North Atlantic.

The same relationship has been found to exist between *G. hirsuta* (d'Orbigny) and *G. punctulata* (d'Orbigny). Since *G. punctulata* has priority over *G. hirsuta*, we are taking *G. p. punctulata* to be the nominate subspecies.

The cores considered in this paper were taken in areas within which *G. m. menardii* is presently abundant and dominant over *G. m. tumida*. Lower in the section the relationship is reversed, *G. m. tumida* being dominant over *G. m. menardii*. EMILIANI (1954) has found, by means of oxygen isotope analyses, that *G. m. tumida* registers a lower temperature than *G. m. menardii*. If then *G. m. tumida* is tolerant of cooler water, it seems reasonable to interpret dominance of *G. m. tumida* over *G. m. menardii* as an indication of cooler climate than that of the present.

The next lower well-defined faunal zone is marked by reduction of *G. menardii* (*s.l.*) to rare or absent, and by an abundance of *G. inflata*. Cores taken by the *Meteor* in the equatorial Atlantic reached this same zone of rare or no *G. menardii* (*s.l.*) The top of this zone was considered by W. SCHOTT (1935) to represent the end of the last glacial stage. We believe that recent findings confirm his and OVEY's (1950) conclusions. Age determinations by radiocarbon (Fig. 8) of samples from the boundary layer agree satisfactorily with the date of the close of the Würm (Wisconsin) glacial stage as obtained by BRAMLETTE and BRADLEY (1940), and WISEMAN (1954). The evidence from our much longer cores shows that this was indeed a major

climatic change which lasted for many tens of thousands of years. By this assumption we gain a valuable criterion by which to distinguish glacial from interglacial stages, even in the equatorial region where, all else being equal, the climatic

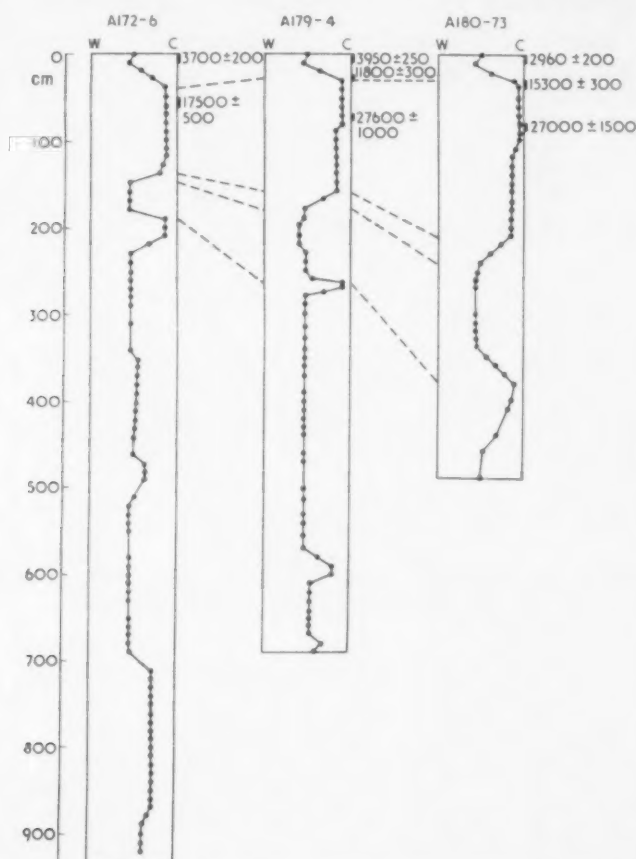


Fig. 8. Correlation of faunas in the Caribbean cores, A172-6 and A179-4, and a core from the equatorial Atlantic. The curves are based on the proportion of the number of warm-water to cold-water planktonic Foraminifera. *W* indicates relatively warm climate and *C* relatively cold climate. The blacked-out zones indicate the parts of the cores which were sampled for radiocarbon age determinations. The numbers to the right of the blacked-out zones are radiocarbon dates in years by HANS E. SUESS. The broken lines connect faunal and climatic changes which are considered to have taken place at the same time, the upper one considered to be the end of the Wisconsin (Würm).

The radiocarbon dates give about the same rate of accumulation, 2.2 cm per 1,000 years, during post-Wisconsin time for Core A179-4 and A180-73, but from about 27,000 years to the end of Wisconsin the rate was 3 cm in A179-4 and 4.3 cm in A180-73 per 1,000 years. Correlation of the curves show the same relationship between these two cores. In core A172-6 the radiocarbon date gives a rate of 3.2 cm per 1,000 years for the top 56 cm. The fauna also indicates a greater rate of accumulation during post-Wisconsin time for this core. Further down in core A172-6, however, the changes in fauna and climate indicate a slower rate for this core compared with the other two.

change was probably somewhat less drastic than in higher latitudes. If comparable extremes of climate obtained during the earliest stages of the Pleistocene, they should be recorded by comparable faunal changes.

The base of this zone is rather sharply defined by a layer containing *G. m. flexuosa* in abundance. Since this subspecies is extinct, we have no direct evidence on its temperature tolerance. Because it is close morphologically to *G. m. menardii*, we are tentatively giving it the same weight as *G. m. menardii* as an indicator of warm climate.

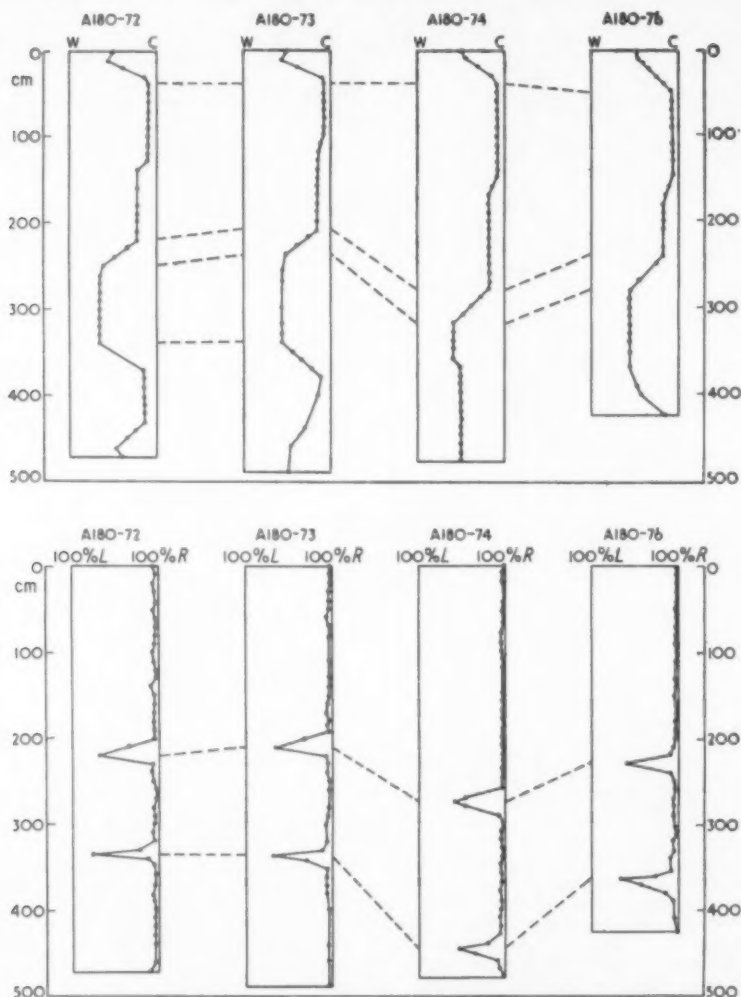


Fig. 9. Correlation of faunas and coiling direction of *Globorotalia truncatulinoides* in the equatorial cores. The curves in the top half of the drawing are based on the proportion of the number of warm-water to cold-water planktonic Foraminifera. *W* indicates relatively warm climate and *C* relatively cold climate. The curves in the lower half of the drawing are based on the ratio in percentage between right and left coiling shells of *Globorotalia truncatulinoides*. *L* indicates left and *R* right.

Comparison of the broken lines which indicate the correlation of changes in fauna and climate with the broken lines which indicate the correlation of changes in the coiling direction of the shells show a relationship. There is some indication that when there was a distinct change in climate there was also a distinct change in the coiling direction of the shells; for example, there is a change from cold to warm at 220 cm, and from warm to cold at 340 cm in core A180-72, and at the same points there are changes in the coiling direction.

The correlations also show that the rate of accumulation was about the same at stations A180-72 and 73, and that it was faster at A180-74 and 76.

The writers consider the following species to be most significant as climatic indicators.

G. m. menardii, *G. m. flexuosa*, and *G. tumida* are particularly characteristic of warm water. *G. p. punctulata*, *G. scitula*, and particularly *Globigerina inflata*, in abundance, are indicative of relatively cold water. *Globigerina bulloides* and *G. pachyderma* occur in great abundance at northern stations in the Atlantic, but in

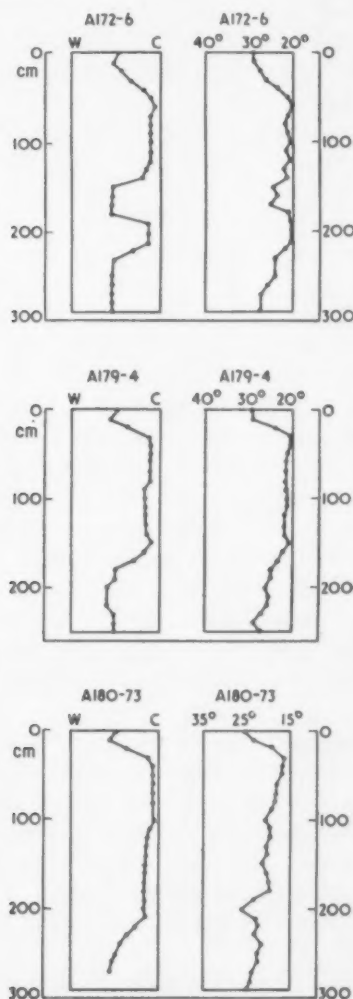


Fig. 10. Comparison of climate determinations by planktonic Foraminifera with temperatures by the oxygen isotope method. The curves with *W* and *C* at the top are based on the proportion of the number of warm-water to cold-water planktonic Foraminifera, *W* indicates relatively warm climate and *C* relatively cold climate. The other curves are based on isotopic temperature data by CESARE EMILIANI; degrees in Celsius. The climate determinations obtained by the different methods correlate well except from part of Core A180-73.

It is assumed that the species of the top sample are adapted to the present climate. This present assemblage is taken as a standard to which assemblages lower in the core are referred. Present climate is plotted on the mid-line, and inferred past climates are plotted with respect to it.

the equatorial and Caribbean cores they are not, we believe, sufficiently abundant at any level in the cores to be of much use as indicators of cold climate. Figs. 8 and 9 show the climatic curves.

Pulleniatina obliquiloculata and *Sphaeroidinella dehiscens* are of somewhat doubtful significance. In the equatorial cores *Pulleniatina obliquiloculata* is very abundant in the lower half of the zone of cool climate. This we interpreted as indicating a climate slightly less cold than that of the upper half, in which the species is absent. On the whole this interpretation is supported by the oxygen isotope data, which show progressive cooling during this time (Fig. 10).

The other species, for example, *Globigerinoides ruber*, *G. sacculifer*, and *Orbulina universa* are either erratic in distribution or are so tolerant of temperature variation that they are useless as indicators. However, for the sake of completeness they have been included in the faunal distribution tables.

CORRELATION

The four equatorial cores are a particularly good example of correlation. When these cores were first inspected, it was evident from the colours of the various sediment layers that there was at least a gross lithological correlation (Fig. 6).

Weighing and sieving of samples for palaeontological study has shown that the percentage of material coarser than 74 microns varies correspondingly from core to core (Fig. 6). This in itself is good evidence of slow particle by particle deposition, undisturbed by turbidity currents or any process such as slumping or current scour. It is hardly conceivable that these agents could have worked simultaneously and uniformly at four stations widely separated in depth and horizontal distance.

Microscopic examination of the washed material has yielded evidence confirming the identification of layer 8 (Fig. 6) in the four cores. It was found to contain frustules of a large diatom, *Ethmodiscus* sp., in abundance. Nowhere else in the cores does this form occur, except rarely.

Two more layers are identifiable in the four cores by an independent criterion, that is, the coiling direction of *G. truncatulinoides* (BOLLI, 1950; 1951, ERICSON, *et al.*, 1954).

Thanks to these independent checks by means of lithology, particle size fraction, and coiling direction of *G. truncatulinoides*, we are confident that the gross faunal variations from which we have inferred climatic changes are real, and afford a reliable record of regional climatic variation during the late Pleistocene. Correlation of the inferred climatic curves in these four cores is shown by Fig. 9.

Can these correlations be extended 6,000 km and into the Caribbean?

The diatom layer we can eliminate at once. It is quite absent from the Caribbean cores.

Fig. 11 shows comparison of curves of coiling direction of *G. truncatulinoides* in the Caribbean cores and one of the equatorial cores. Evidently no close correlation exists between the equatorial and Caribbean, or even between the two Caribbean cores. The well defined point at 170 cm in A179-4 is absent from A172-6. This might have been predicted from recent distribution of coiling in the Caribbean. There is much variation there from place to place. On the other hand, in the equatorial region the coiling is over 90 per cent right throughout. Presumably conditions influencing coiling in the equatorial region are and have been fairly uniform.

The 74 micron fraction gives a rather strikingly good correlation between A180-73, the equatorial core, and A179-4, the most remote of the two Caribbean cores. Correlation with A172-6 is less satisfactory, but there is at least some correspondence between the curves.

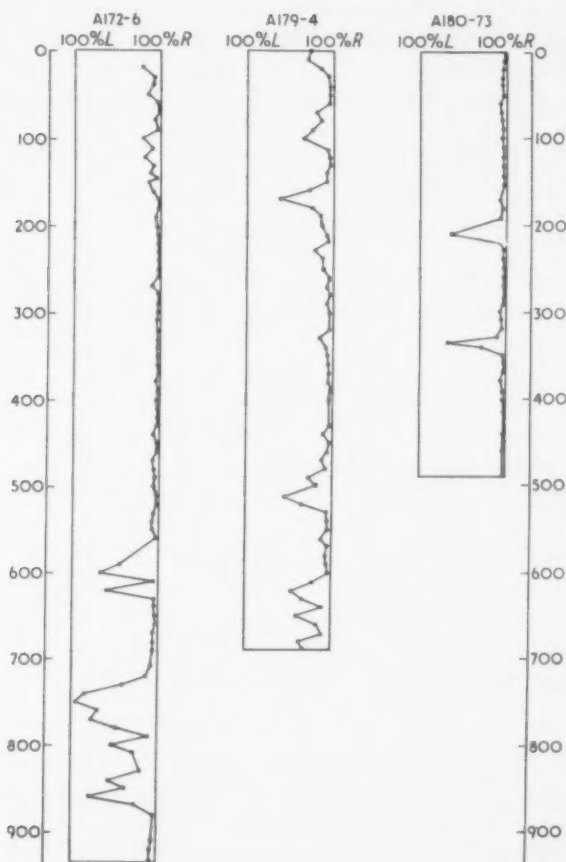


Fig. 11. Comparison of the coiling direction of *Globorotalia truncatulinoides* in the Caribbean cores, A172-6 and A179-4, and a core from the equatorial Atlantic. The curves are based on the ratio in percentage between right and left coiling shells. *L* indicates left and *R* right. Evidence of some correlation can be seen.

Fig. 8 shows correlation between climatic curves. Here the correspondence between the Caribbean cores is excellent, and that between them and the equatorial core is good.

CONCLUSIONS

Correlation by variation in coiling direction of *G. truncatulinoides* is reliable in the equatorial region over distances in the order of at least 500 km. However, correlation between the equatorial region and the Caribbean by this means is not satisfactory.

Correlation by variation in percentage of coarse material (74 microns) is an

effective method of correlation in the equatorial region, and may even be extended 6,000 km into the Caribbean.

The most reliable method of correlation between the equatorial region and the Caribbean is by climatic zones inferred from variations in numbers of certain temperature-sensitive species of planktonic foraminifera.

Climatic zones based on study of the planktonic foraminifera are in good agreement with water temperatures obtained by the oxygen isotope method.

Radiocarbon age determinations show that the rate of sediment accumulation in the equatorial region varies from 2.2 cm per thousand years to 4.3 cm per thousand years. It is at least suggestive that the rapid rate of accumulation took place during the latter part of Wisconsin time. A similar relationship, but in less degree, is found in one core (A179-4) from the Caribbean.

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Lamont Geological Observatory, Columbia University. Contribution No. 167.

REFERENCES

- BOLLI, H. (1950), The direction of coiling in the Evolution of some Globorotaliidae. *Cushman Found. Foram. Research Contr.*, **1**, 82-89.
- BOLLI, H. (1951), Notes on the Direction of Coiling of Rotalid Foraminifera. *Cushman Found. Foram. Research Contr.*, **2**, 139-143.
- BRAMLETTE, M. N. and BRADLEY, W. H. (1940), Geology and Biology of North Atlantic deep-sea cores, Pt. 1, Lithology and geologic interpretations. *U.S. Geol. Surv., Prof. Paper 196-A*, 1-34.
- CUSHMAN, J. A. and HENBEST, L. G. (1940), Geology and biology of North Atlantic deep-sea cores, Pt. 2. Foraminifera. *U.S. Geol. Surv., Prof. Paper 196-A*, 35-50.
- EMERY, K. O. and DIETZ, R. S. (1941), Gravity coring instrument and mechanics of sediment coring. *Geol. Soc. Amer. Bull.*, **52**, 1685.
- EMILIANI, C. (1954), Depth habits of some species of pelagic Foraminifera as indicated by oxygen isotope ratios. *Amer. J. Sci.*, **252**, 149-158.
- ERICSON, D. B., EWING, M. and HEEZEN, B. C. (1952), Turbidity currents and sediments in the North Atlantic. *Amer. Assoc. Petrol. Geol. Bull.*, **36**, 489-511.
- ERICSON, D. B., WOLLIN, G. and WOLLIN, J. (1954), Coiling direction of *Globorotalia truncatulinoides* in deep-sea cores. *Deep-sea Res.*, **2**, 152-158.
- KOCH, R. (1923), Die jungtertiäre Foraminiferenfauna von Kabn. *Eclogae Geol. Helv., Lausanne*, **18**, (2), 357.
- KUENEN, PH. H. (1950), *Marine Geology*. John Wiley & Sons, Inc., New York, 568 pp.
- KULLENBERG, B. (1947), The piston core sampler. *Svenska Hydr.-Biol. Komm. Skr., Tr. Hydr.* **1**, (2), 1-46.

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- PHLEGER, F. B., PARKER, F. L. and PIERSON, J. F. (1953), North Atlantic Foraminifera. *Swedish Deep-Sea Expedition Repts.*, 7, (1), 122 pp.
- PIGGOT, C. S. (1941), Factors involved in submarine core sampling. *Geol. Soc. Amer. Bull.*, 52, 1513-1523.
- PRATJE, O. (1934), Sind die Bodenprofile aus den Röhrenloten ohne Unterbrechungen? Versuche über die Arbeitsweise der Röhrenlote. *Ann. Hydr. Mar. Met.*, 62, 137-144.
- PRATJE, O. (1939), Die Sedimentation in der südlichen Ostsee. *Ann. Hydr. Mar. Met.*, 67, 209-221.
- SCHOTT, W. (1935), Die Foraminiferen in den aquatorialen Teil des Atlantischen Ozeans. *Deutsche Atlantische Exped. Meteor 1925-1927*, 3, (3), Lief 1B, 43-134.
- SHEPARD, F. P. (1948), *Submarine Geology*. Harper and Bros., N.Y. 348 pp.
- WISEMAN, J. D., H. (1954), The determination and significance of past temperature changes in the upper layer of the equatorial Atlantic Ocean. *Proc. Roy. Soc., A* 222, 296-323.

Rock fragments and pebbles dredged near Jimmu Seamount, northwestern Pacific

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Abstract—Fifty-five rock fragments and pebbles were dredged at 2,550-2,800 fathoms (4,650-5,100 metres) near Jimmu Seamount, 700 miles southeast of Kamchatka. Tuffaceous shale, andesitic and dacitic tuff, pyroxene-hornblende dacite-pumice, and augite-hypersthene andesite are the most abundant rock types. Minor constituents in the haul include augite-pigeonite basalt, augite-olivine basalt, olivine dolerite, quartz syenite porphyry, metabasalt, sandstone, and chert. Petrographic and chemical analyses indicate closer affinities with Kuril Islands and Kamchatka volcanic rocks than with Cenozoic Japanese or Pacific Basin types. Probably these rocks were dropped by Pleistocene icebergs carried south and east by ocean currents.

INTRODUCTION

THE University of California R/V *Spencer F. Baird* visited Jimmu Seamount in September 1953, while engaged in the Hydrographic and Biological Trans-Pacific Expedition to the Western Pacific (Fig. 1). The samples discussed below were collected by biological dredge from the northwest flank of the seamount, at a depth of 2,550-2,800 fathoms (4,650-5,100 metres). The petrographic examination of these samples was made at the Geological Institute, Tokyo University.

From the expedition fathograms, Jimmu Seamount appears to be a guyot or tablemount, with a least depth of 700 fathoms (1,280 metres) and a principal break in slope at 830 fathoms (1,520 metres). The flat top probably indicates truncation by wave action when the summit was at or very near the sea surface.

Jimmu Seamount is one peak on a north-south submarine range which DIETZ (1954, p. 1209-11) has designated the Emperor Seamounts. The south end of the range apparently joins the western end of the Hawaiian Swell. Three guyots of this range are shown on the profile in Fig. 1, from a Trans-Pacific Expedition fathogram. The summits of the three peaks are not accordant. DIETZ, among others, favours local isostatic subsidence of such peaks; according to this view the greater submergence of the southernmost guyot need not indicate greater age.

PETROGRAPHIC DESCRIPTION

Fifty-five rock fragments and pebbles were dredged from near the base of Jimmu Seamount. Nineteen are flat, angular fragments of comparatively soft rocks (Nos. 1-19, Fig. 2a), ten are well-rounded pumice (Nos. 20-29, Fig. 2b), twenty-four are well-rounded pebbles of hard rocks (Nos. 30-53, Figs. 3a and 3b), and two are ragged fragments of scoria and slag (Nos. 54 and 55, Fig. 3b). Thirty-six thin sections were cut from representative specimens of these rocks.

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A. Angular fragments (Fig. 2a)

Most of the angular fragments consist of light grey or yellowish grey shale and tuff of salic andesite or dacite. Much of the shale is tuffaceous. Quartz syenite porphyry and quartz gabbro are also represented. The former consists of orthoclase-perthite, albite, quartz, and altered mafic minerals; the latter is strongly weathered.

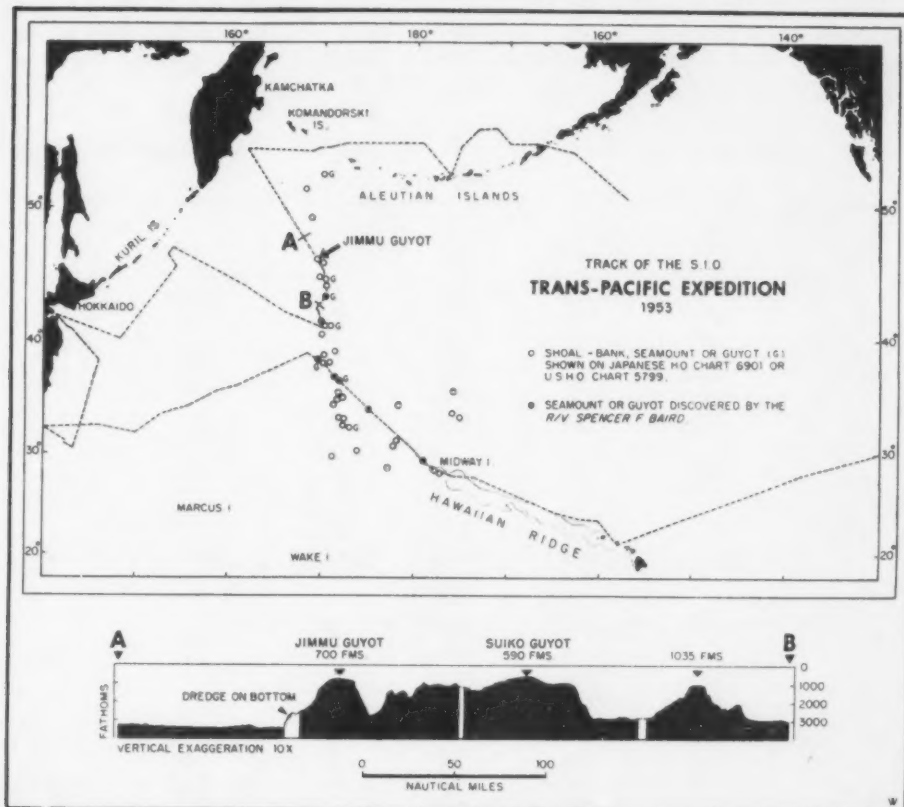


Fig. 1.

The fragments are coated with a thin black film, probably of manganese oxide. Small fragments are attached to the surface of larger pieces of the same rock. Calcareous tubes of Annelida adhere to the surfaces of some of this suite. The larger white tubes (No. 18) are those of *Serpulinae*, while smaller brownish ones (Nos. 12, 13, and 14) are those of *Amphiteis* sp. These tubes do not give any information as to the source of the fragments because allied species of annelida have been obtained from various parts of the Pacific Ocean, between the depths of 345 and 3,125 fathoms (oral communication by HORIKOSHI). As the tubes look very fresh and cover the surface of the black film, they were probably formed after the fragments were emplaced in their present position.

B. Pumice (Fig. 2b)

The pumice has a nearly uniform petrographic character. It is pyroxene-hornblende

dacite with phenocrysts of medium plagioclase, augite, hypersthene, green hornblende, and magnetite, although pyroxenes or hornblende are absent in some specimens. Quartz phenocrysts are only found in one of the slides. The groundmass consists of colourless glass entirely free of devitrification. A chemical analysis of one of the dacites (No. 27) is given in Table 1.

Small xenoliths of tuffaceous sandstone, biotite-hornblende gneiss, and olivine-augite-anorthite basalt are present in some specimens. Some of the cavities of the pumice are filled with radiolarian ooze which obviously was deposited after the pumice was dropped in its present position.

Table 1. Chemical composition of the pebbles dredged from Jimmu Seamount, north-western Pacific.

Specimen No.	36	41	54	49	34	27
SiO ₂	45.90	48.63	52.33	53.85	60.38	71.96
Al ₂ O ₃	16.76	18.06	17.27	18.72	16.98	13.76
Fe ₂ O ₃	5.27	4.01	4.27	3.44	2.93	0.69
FeO	5.25	7.52	4.01	4.90	3.66	1.19
MgO	7.06	5.11	5.93	4.78	3.26	0.55
CaO	10.08	11.23	10.22	8.87	6.61	2.38
Na ₂ O	2.98	2.15	2.80	3.24	2.93	4.38
K ₂ O	1.38	0.48	1.31	0.82	1.53	1.95
H ₂ O (+)	2.09	1.09	0.58	0.34	0.65	1.61
H ₂ O (-)	1.01	1.06	0.32	0.12	0.30	0.45
TiO ₂	1.77	0.72	0.66	0.84	0.60	0.23
P ₂ O ₅	0.48	0.20	0.29	0.20	0.16	0.09
MnO	0.23	0.23	0.30	0.23	0.16	0.14
Total	100.26	100.49	100.29	100.35	100.15	100.14*
Norm						
Q	—	2.46	—	5.58	18.00	32.94
Or	8.34	2.78	7.78	5.00	8.90	11.68
Ab	23.58	17.82	23.58	27.25	24.63	36.68
An	28.36	38.36	30.86	33.92	28.91	10.84
Ne	0.85	—	—	—	—	—
C	—	—	—	—	—	0.51
Wo	7.54	6.84	7.54	3.94	1.28	—
En	5.80	12.80	14.80	12.00	8.20	1.40
Fs	0.92	9.64	3.17	5.28	3.56	1.58
Fo	8.40	—	—	—	—	—
Fa	1.43	—	—	—	—	—
Mt	7.66	5.80	6.26	4.87	4.18	0.93
Il	3.34	1.37	1.37	3.80	1.22	0.46
Ap	1.34	0.34	0.67	0.34	0.34	0.34

No. 36 Augite-olivine basalt (trachybasaltic).

No. 41 Augite-pigeonite basalt.

No. 54 Hornblende-olivine-augite andesite.

* Including 0.76 NaCl.

No. 49 Olivine-hypersthene-augite andesite.

No. 34 Olivine-hypersthene-augite andesite.

No. 27 Hornblende dacite-pumice.

Analyst: T. KATSURA.

C. Pebbles (Figs. 3a and 3b, upper)

The hard-rock pebbles comprise a varied suite: pyroxene andesites (8 specimens), basalts (2), altered olivine dolerite (1), metabasalt (1), tuffs (2), shales and tuffaceous shales (7), sandstone (1), and chert (2).

The andesites contain phenocrysts of labradorite, augite, hypersthene, and magnetite, occasionally with those of olivine or hornblende. Xenocrysts of quartz are



Fig. 2b.

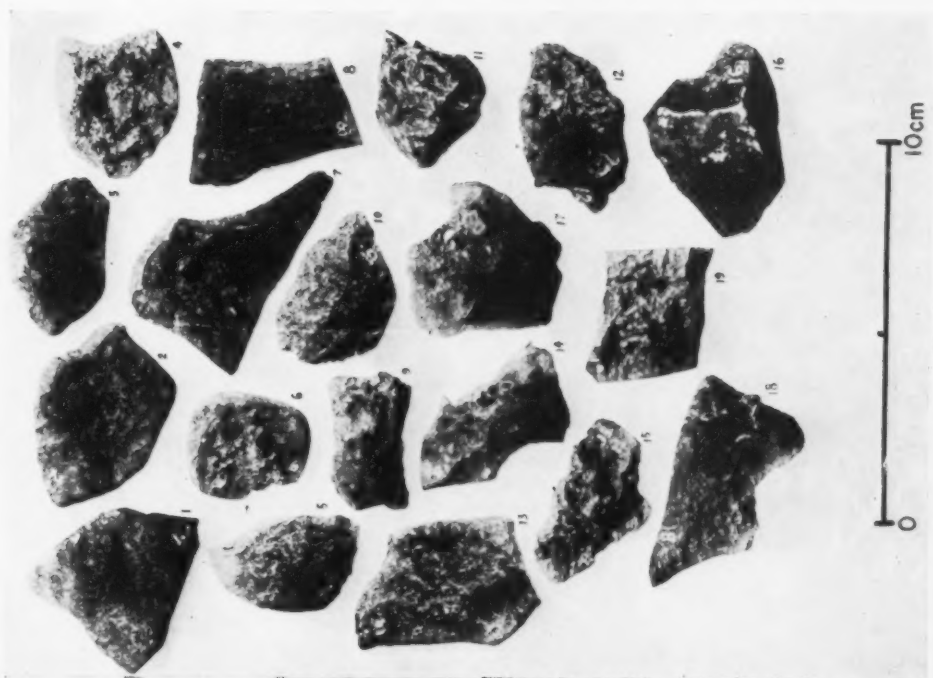
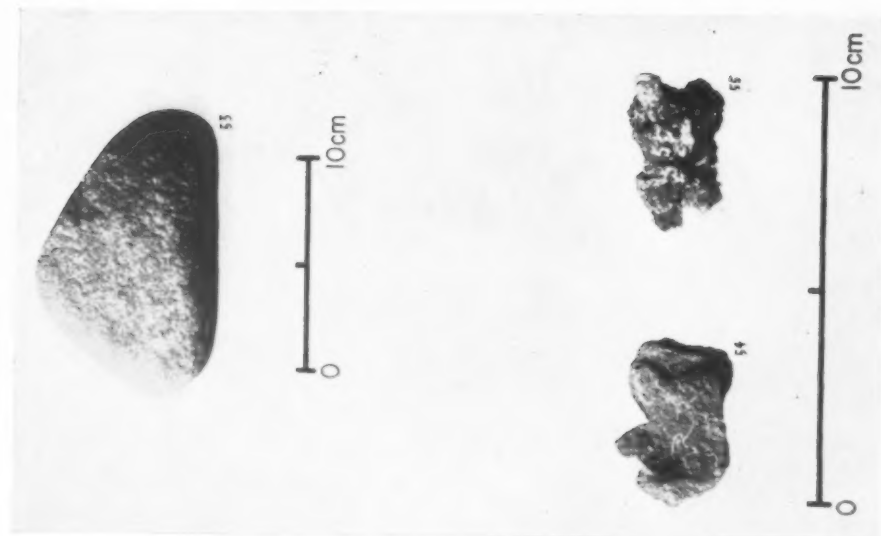


Fig. 2a.



found in one specimen. The groundmass constituents are plagioclase, augite, hypersthene, iron ore, and interstitial glass and quartz. In some rocks, the plagioclase is replaced by albite while the mafic minerals are changed to chlorite. Three fresh andesites (Nos. 34, 39, and 54) were selected for chemical analysis with the result given in Table 1.

One of the basalts is an augite-pigeonite basalt, containing phenocrysts of bytownite, pigeonite, augite, and a little hypersthene, in a groundmass consisting of a feathery aggregate of labradorite, augite, and iron ore, with interstitial dark brown glass. The occurrence of porphyritic pigeonite in basalt is rather unusual; in most cases porphyritic pigeonite is found in andesite and dacite representing late differentiates of tholeiitic magma (KUNO, 1950). As seen from the analysis (No. 41) given in Table 1, the rock has a high $\text{FeO} + \text{Fe}_2\text{O}_3/\text{MgO}$ ratio, low alkalis, and a little normative quartz in spite of low SiO_2 . These features agree with the general characteristics of tholeiitic basalt. Basalts with similar composition but not with similar mineral assemblage are quite common in Japan.

The other basaltic specimen is an olivine- and augite-bearing type, of trachybasaltic affinity. An undersaturated, slightly alkalic rock, it contains phenocrysts of bytownite, augite, and olivine, set in a groundmass consisting of labradorite, augite, olivine, magnetite, apatite, and interstitial alkali-feldspar. The olivine is entirely replaced by chlorite or saponite. As seen from the analysis (No. 36, Table 1), the rock has low SiO_2 and relatively high alkalis, yielding a considerable amount of normative olivine and a little nepheline.

The olivine dolerite has coarse ophitic texture and consists of albitized plagioclase, titanite, olivine replaced by chlorite or saponite, magnetite, ilmenite, and interstitial zeolite. It has a composition probably approximate to that of the olivine-augite basalt No. 36.

All of the mafic minerals in the metabasalt have been changed to actinolite, while plagioclase is less altered. Schistosity due to parallel arrangement of the actinolite is developed along planes of shearing.

The pyrogenetic material of the tuffs (coarse tuffs) and tuffaceous shales is andesite or trachyandesite. One of the tuffs has been slightly mylonitized.

The sandstone contains angular grains of quartz, plagioclase, biotite, muscovite, and epidote, apparently derived from granitic or gneissose rocks.

The chert is a cryptocrystalline variety, consisting of extremely fine grains of quartz.

D. Scoria and Slag (Fig. 3b, lower)

The ragged fragment of scoria is glassy olivine-hornblende-augite andesite. The slag fragment probably was dropped from a steamship.

PETROGRAPHIC SIMILARITIES OF DREDGED VOLCANIC ROCKS TO INTRA-PACIFIC AND CIRCUM-PACIFIC VOLCANIC SUITES

It is evident from the above descriptions that the mineralogy and chemistry of the volcanic rocks dredged near Jimmu Seamount bear little resemblance to those of the volcanics characterizing the Intra-Pacific region, but agree almost exactly with those of the Circum-Pacific volcanic zone. Basalts similar to No. 36 in Table 1 may occur in the Intra-Pacific region, while such rocks are also found occasionally in the Circum-Pacific Zone.

To demonstrate that the chemical compositions of the rocks in question lie within the variation range of the Circum-Pacific volcanic rocks, a variation diagram for alkalis has been constructed (Fig. 4), using the compositions of the rocks of the Katmai region, Alaska (FENNER, 1926), those of Adak and Kanaga Islands, Aleutian Islands (COATS, 1952), and the average compositions of Japanese volcanic rocks (TANEDA, 1952).

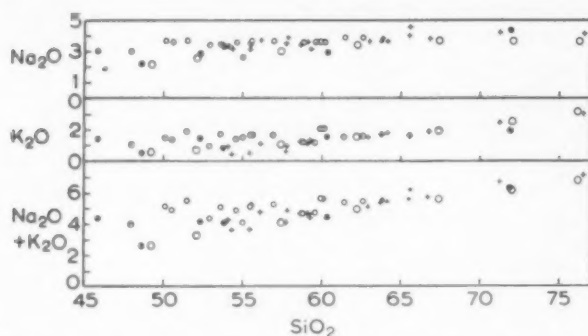


Fig. 4. Variation diagram for alkalis of the volcanic rocks dredged from Jimmu Seamount (black circles), the rocks of Katmai region (crosses), the rocks of Adak and Kanaga Islands (small open circles), and the average compositions of Japanese volcanic rocks (large open circles).

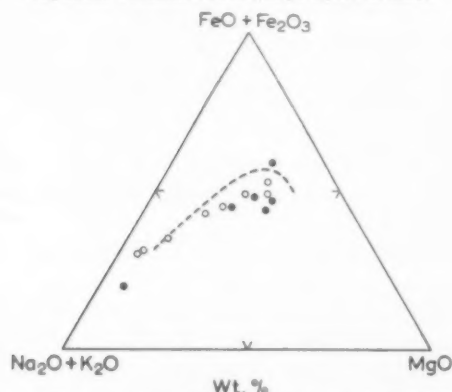


Fig. 6. Plot of the oxides ($\text{FeO} + \text{Fe}_2\text{O}_3$), MgO , and $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ of the volcanic rocks dredged from Jimmu Seamount (black circles) and of Kamchatka (open circles). The broken line represents the boundary between the field of the pigeonitic rock series of Japan (above) and that of the hypersthene rock series (below).

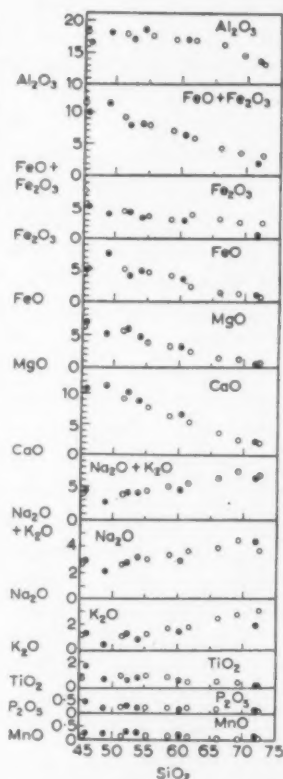


Fig. 5. Variation diagram of the volcanic rocks dredged from Jimmu Seamount (black circles) and the average volcanic rocks of Kamchatka (open circles).

In Fig. 5, the composition of the Jimmu pebbles is compared with the average compositions of volcanic rocks of Kamchatka given in Table 2. A close agreement between the compositions of the pebbles and those of the Kamchatkan rocks is evident from the figure. The augite-olivine basalt (No. 36 of Table 1) is approximate in composition to the average picrite-basalt of Kamchatka (column 1 of Table 2). The pigeonite basalt (No. 41) shows a slight departure from the trend of the Kamchatkan rocks.

The compositions of the Jimmu pebbles and the Kamchatkan rocks are plotted in the triangular diagram (Fig. 6). Except for the pigeonite basalt which lies rather close to the $\text{FeO} + \text{Fe}_2\text{O}_3$ corner of the triangle, the rocks of the pebbles and of Kamchatka show a trend characteristic of the calc-alkali rock series (TILLEY, 1950) or the hypersthene rock series (KUNO, 1953). These rock series are thought to be formed through contamination of magmas by sialic materials (TILLEY, 1950; KUNO, 1950). The pigeonite basalt lies within the field of the pigeonitic rock series (KUNO, 1953) which, it is considered, is formed through fractional crystallization of tholeiitic magma (KUNO, 1950).

Table 2. *Averages of chemical analyses of volcanic rocks of Kamchatka. After VLODAVETS (1939, 1946), quoted in TOMKEIEFF's paper (1949).*

	1	2	3	4	5	6	7	8.
<i>Number of Analyses</i>	3	59	37	19	16	15	4	11
SiO_2	45.54	51.47	55.37	58.68	61.64	66.17	69.31	72.41
Al_2O_3	18.37	17.91	17.64	16.93	16.84	16.05	14.46	13.15
Fe_2O_3	7.69	4.44	3.77	3.03	3.93	3.09	2.47	2.54
FeO	4.46	5.01	4.57	4.15	2.31	1.34	1.31	0.78
MgO	6.27	5.74	3.96	3.20	2.32	1.33	0.71	0.56
CaO	10.61	9.12	7.72	6.30	5.23	3.62	2.45	1.98
Na_2O	2.70	2.64	3.04	3.34	3.66	3.83	4.47	3.69
K_2O	1.17	1.03	1.24	1.73	1.75	2.48	2.78	3.07
$\text{H}_2\text{O} (+)$	2.32	1.42	1.34	1.45	1.52	1.37	1.63	1.42
$\text{H}_2\text{O} (-)$	0.75	0.87	0.96	0.83	0.48	0.47	0.38	0.28
TiO_2	—	0.22	0.26	0.24	0.21	0.17	—	0.06
P_2O_5	—	0.13	0.13	0.12	0.11	0.08	0.03	0.06
MnO	0.12	0.13	0.13	0.12	0.11	0.08	0.03	0.06
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1. Picrite-basalt.

2. Basalt.

3. Andesite-basalt.

4. Andesite.

5. Andesite-dacite.

6. Dacite.

7. Rhyolite-dacite.

8. Rhyolite.

The dredged volcanic rocks are also very similar in composition to those of Kuril Islands. The basalt No. 36 and the olivine-augite anorthite basalt found as xenoliths in the dacite-pumice are mineralogically very close to some lavas of Alaid Volcano, at the northern end of the island arc (KUNO, 1935).

PROBABLE SOURCE OF THE ROCK FRAGMENTS AND PEBBLES

Only two modes of origin of the rocks dredged from the flank of Jimmu Seamount need be considered. One possibility is that they are locally-derived, representing debris slumped from the top of the seamount when it was cut by wave erosion. The seamount may have been composed of a variety of rocks, volcanic, plutonic, sedimentary, and metamorphic; or it may have been a volcanic cone made up of a rather simple association of volcanic rocks, the other rock types having been torn from the basement rocks by explosive eruption and interbedded with the lavas as pyroclastic layers. On this interpretation the minerals comprising the sandstone would indicate the existence of sialic material in the source region. Likewise, as has been stated, the andesites and dacites would have been formed by incorporation

of sial in the magma. However, as the existence of the sialic layer in the Jimmu region is very improbable, if not yet disproved by geophysical data, the derivation of the rock fragments and pebbles from the adjacent seamount is unlikely.

The other possibility is that these rocks were transported by Pleistocene icebergs from some region belonging to the Circum-Pacific volcanic zone and were dropped at the present location upon melting of the ice. The rounded pebbles are probably beach or river gravels which were captured by the glaciers.

In Hokkaido, at the northern end of the Japanese Islands, Pleistocene glaciers were present only on mountains higher than 1,500 metres (4,900 feet), while such glaciers appear to have existed even near sea level in the Kuril Islands (oral communication by Sasa). In Kamchatka, glaciers still exist on mountains higher than about 1,500 metres, and during Pleistocene time they extended down to the sea coast (VON REINHARD, 1915; KLEBELSBERG, 1948). It is likely therefore that icebergs derived from the Pleistocene glaciers of Kamchatka or the Kuril Islands were carried first southward by the cold ocean current and then eastward until they reached the vicinity of Jimmu Seamount. The similarity in petrographic character of the volcanic rocks found as pebbles at Jimmu to those of Kamchatka and of the Kuril Islands supports this interpretation. If oceanic circulation in the North Pacific during Pleistocene time was similar to the present pattern, possibly displaced southward slightly, icebergs originating in Alaska or the Aleutian Islands would not have reached Jimmu Seamount because of the warm current flowing eastward and southeastward.

The possibility that light pumice from volcanoes in the Japanese Islands was transported to Jimmu Seamount by the warm ocean current cannot be excluded entirely.

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REFERENCES

- COATS, R. R. (1952), Magmatic differentiation in Tertiary and Quarternary volcanic rocks from Adak and Kanaga Islands, Aleutian Islands, Alaska. *Bull. Geol. Soc. Amer.*, **63**, 485-514.
- DIETZ, R. S. (1954), Marine geology of Northwestern Pacific: description of Japanese bathymetric chart 6901. *Bull. Geol. Soc. Amer.*, **65**, 1199-1224.
- FENNER, C. N. (1926), The Katmai magmatic province. *J. Geol.*, **34**, 673-772.
- KLEBELSBERG, R. (1948), *Handbuch der Gletscherkunde und Glaciologie*, 467 and 764.
- KUNO, H. (1935), Petrology of Alaid Volcano, North Kurile. *Jap. J. Geol. Geogr.*, **12**, 153-162.
- KUNO, H. (1950), Petrology of Hakone Volcano and the adjacent areas. *Bull. Geol. Soc. Amer.*, **61**, 957-1020.

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- KUNO, H. (1953), Formation of calderas and magmatic evolution. *Trans. Amer. Geophys. Union*, **34**, 267-280.
- TANEDA, S. (1952), New average chemical compositions of Japanese effusive rocks. *J. Geol. Soc. Japan*, **58**, 517-521.
- TILLEY, C. E. (1950), Some aspects of magmatic evolution. *Quart. J. Geol. Soc. London*, **106**, 37-61.
- TOMKEIEFF, S. I. (1949), The volcanoes of Kamchatka. *Bull. Volcanologique, Ser. 2*, **8**, 87-113.
- VON REINHARD, A. (1915), Über die eisseitliche Vergletscherung Kamschatkas nach den Beobachtungen von W. Komarou. *Z. Ges. Erdk. Berlin*, 180-183.

The difference between sliding and turbidity flow

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Abstract—The table at the end of this paper summarizes the findings.

INTRODUCTION

SUBAQUEOUS sliding or slumping and turbidity currents are frequently mentioned together, and sometimes they are treated as practically identical phenomena. In the following note an attempt is made to bring out the difference and to find the physical basis for the dissimilarity of the two kinds of movement. Most of what follows has already been brought forward in earlier papers of the author, but it is hoped that the present review may help to clarify thought on this subject.

Rock falls in which blocks of more or less consolidated rock move independently or in swarms will not be considered here. Only the mass movement of unconsolidated sediment on a subaqueous slope under the influence of gravity will be examined.

SLIDING OR SLUMPING

The deposit from a slide can have any granulometric composition, such as pure mud, sandy mud, gravel with sand and mud, or a mixture of boulders with finer material. Commonly lutite forms a conspicuous ingredient, because clean sands and gravels tend to accumulate in stable deposits which will not easily start to slide. There is no, or hardly any, segregation of the larger particles towards the bottom of the deposit. It is known that one can walk on the boulders protruding from the surface of an active mud flow on land. C. DURRELL has shown the writer a large subaqueous slump in Split Mountain Canyon in Southern California. This mass, 30 metres thick and visible as a sheet over considerable distances, had bored itself into the underlying stratified sand, buckling the latter into a sizable anticline several dozen metres high. All these phenomena point to a paste-like condition of a slide while it is in motion, as does the steep nose characteristic of some slump deposits.

Mud flows on land are known to display a wide range of velocities, from creep that shows up only after years of observation to velocities of several kilometres per hour. There are even watery slumps which rival avalanches in speed.

Dependent on the relative amount of water there appear to be all transitions from mud flows to flows of water with a high percentage of suspended sediment. Thus the catastrophic deluges following the eruptions of Mount Kelud on Java, in the course of which the crater lake was flung over the rim of the crater, are known to have left huge boulders perched above the ground between the branches of trees. Hence the density of the flow must have been very high. Yet the fact that those trees were not

carried away and that the bulk of the sediment was transported to the surrounding plains, testifies to the mobile condition of these flows. The writer assumes that no thixotropic strength had been built up in these flows, and that they resembled turbidity currents in this respect.

This type of dangerously swift flash flood is not a normal subaerial slide. The mechanism, of which very little is known, will not be considered here.

Returning to subaqueous slumping, this can cause strongly varied degrees of reconstitution of the original strata, from mere distortion with or without rupturing to kneading and balling up of sandy parts embedded in clay, thus producing a slump sheet, or even to complete remixing in a typical mud flow. This will depend on the unevenness and slope of the substratum, on the distance of transport relative to the size of the moving mass, and on the constitution of the slumping sediments. In a moving mudflow a kind of slow boiling agitation takes place. One can therefore say that the flow is turbulent, but the high viscosity renders the motion rather different from the turbulence of a river.

Slides can show all manner of shapes and sizes. At the high end there should normally be some kind of niche, and there may be an area with cracks and pull-apart structures. The bed of the slide tends to be grooved parallel to the movement down slope. The slump mass may have moved right away from the niche or it may still fill the bottom of this hollow. At the far end of the slide the slumped material is more or less heaped together. Watery slides, however, can spread out in a wide fan.

Although a slide may have affected only a single bed, there are countless cases in which two or several beds have moved together.

Various geologists have expressed the opinion that slides may take place under a cover of sediment which does not partake in the movement. But O. T. JONES has shown that some slides are covered by a graded bed welded to the surface. In other instances the irregularities of the surface are filled in with laminated sediment. Or, again, the upper surface may show erosion of the soft-rock anticlines. In all such occurrences the slide must evidently have been "open cast."

In a few exceptional cases some sediment may be locally squeezed out from under a consolidated overburden, but the type of internal deformation of such masses must be quite different, with drag both along the lower and upper surfaces. The movement ends when the overburden comes to rest on the substratum. If there is sufficient slope for the mobile stratum to move laterally through its own weight, instead of being squeezed out from under the overburden, then the latter must lose support, crack and break away. The pieces slide down on the remains of the supporting mobile layer which acts as a lubricant. These considerations lead the present author to assume that all slides are "open cast." The term slide or slump had better not be applied to the squeezing-out process.

An important property of slides is that they come to a stop more or less suddenly and virtually at the same moment throughout the entire mass. Through compaction water may be lost after the movement has ceased, even from a subaqueous slide. But by and large the whole mass moves and halts as a single unit, and does not change significantly afterwards. In this respect there is a strong contrast with turbidity currents.

A subaqueous slide meets with more friction along its base than its surface, and because of uniform density gravity acts equally on the whole thickness. Hence it will show the highest velocity at its surface. It tends to be directly overlain by clear water. Fissures may develop as in a glacier, but the amount of water taken up by the mass is relatively small.

A slide requires a slope to set it off and keep it going. Under certain favourable conditions the minimum angle appears to be as low as 1° or 2° , but thick beds of deep-sea deposits are encountered on slopes considerably steeper. Some continental slopes appear to be active sites of sedimentation, although the declivity is several degrees. Others are more or less non-depositional. The most suitable slope for accumulation of marine lutite interrupted by occasional slumps may be estimated at 5° to 10° .

When a sliding mass arrives on a declivity insufficient to keep it in motion, it will come to a stop almost at once in consequence of its high viscosity and low velocity.

TURBIDITY CURRENTS

There is overwhelming evidence that graded marine graywackes, graded detrital limestones, and graded recent deep-sea deposits, have been deposited by turbidity

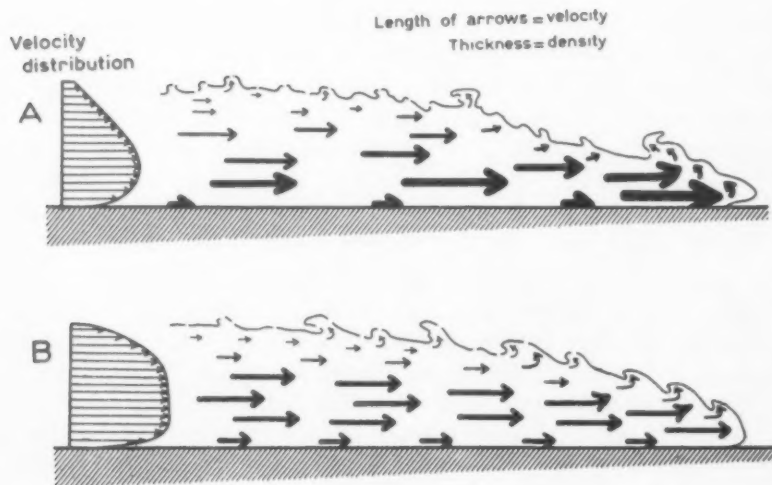


Fig. 1. Diagrammatic section of turbidity currents.

- A. A current with relatively coarse suspended load (or small velocity).
B. A current with relatively fine grained suspended load (or high velocity).

currents. In amongst the beds of a graywacke series or the deep-sea sands of the present ocean floor there are usually a number of beds showing poor grading or none at all, although they have evidently been emplaced by the same mechanism. On the other hand there are some graded rocks which are the result of other processes

such as river action, volcanic explosions, etc. These uncommon occurrences need not concern us here.

The usual grading proves that the grains have settled individually from the current and came to rest on the bottom while the transporting current was still passing over them. Lamination in the finer-grained upper part of many graded beds indicates that the grains were rolled some distance along the bottom. Thereby the selection could take place which is needed to form laminae contrasting somewhat amongst each other in composition.

The deductions from the texture confirm the conclusion arrived at by observing experimental turbidity currents, that the movement is strongly turbulent and that the viscosity is not significantly higher than that of water. This low viscosity was also found in turbulent turbidity currents of high density, e.g. 1.8 and higher, the material of which is pasty when calmly stirred in a bucket before release under water. The explanation must be that the thixotropic strength is broken down during the initial sliding movement, and that once gone it cannot be restored during the resulting turbulent flow.

One effect of the mobility of a turbidity current is that the upper part readily mixes with the overlying water. With a slump this is much less the case although, as stated, the mass may fissure and thus absorb some water. At first the writer had assumed that this mixing with water was the manner in which a slide changed to a turbidity current, but it was afterwards realized that the change can take place by loss of internal cohesion without addition of water, and probably this is the normal way in which it happens (see KUENEN, 1952).

The velocity of a turbidity current decreases from the nose backwards and from near the bottom upwards. This is because the density and therefore the action of gravity varies in the same manner. In consequence of the gradual decrease in density towards the upper level there is no density jump at the surface. Hence the turbulence results in a curly surface, recalling astrakhan fur. This surface moves relatively slowly in consequence of friction with the overlying water. The gradual transition from an almost stagnant dilute surface to the dense, swift core of the current was observed in the experiments. It should reduce the development of boundary waves, and may be the secret of the high velocities.

The current loses part of its load to form this transitional zone. The relative amount of loss must depend on various factors, but need not be drastic, especially as coarser particles should tend to drop back into the main body of the current.

Another aspect of the flow is that the heavy nose wedges its way under the stagnant clear water.

A turbidity current can have attained a high velocity on a steep slope ; or it may contain no coarse load, either because no large grains were available, or because the coarser particles have already settled out. In both these cases the turbulence will be able to keep the load from concentrating near the bottom. Hence the density will show less variation in a vertical and horizontal sense. However, the upward transition from the dense core of the current to the clear, surrounding water will remain.

It is almost certain that most turbidity currents start as slides ; but the lower, denser part of highly turbid rivers discharging on a narrow shelf or in the head of a submarine canyon may possibly continue as a turbidity current.

Although it has not yet been proved, it appears likely that on a steep slope a turbidity current can pick up unconsolidated sediment. The moot question whether semi-consolidated sediment can be eroded need not be raised here. Towards the lower end of the slope, as the declivity begins to diminish, deposition starts. The absence of the finer grained top part from many graded beds covered by pelagic clay shows that on sufficient slope the dilute tail of the current can pass on without depositing its load of lutite.

It is mainly through the efforts of EWING and his collaborators that a large body of evidence has been gathered indicative of the great importance of turbidity currents in the Atlantic and the Gulf of Mexico. MENARD has confirmed this for the northeast margin of the Pacific. For the Mediterranean similar evidence is becoming available. A sound working hypothesis, to say the least, has been evolved according to which turbidity currents carrying lutite can pass out a hundred miles and probably much further across almost horizontal abyssal plains. The slope there is so slight that a significant part of the driving force is due to the gradual spreading and thinning out of the cloud of turbid water.

TRANSITIONAL TYPES OF MOVEMENT

It was pointed out above that flash floods may in all probability result in a high-density, non-viscous flow strongly resembling a turbidity current in its motion.

The question arises : is there a difference between a turbidity current and the bottom water of a river in spate, strongly charged with suspended sediment ? There is one essential distinction. The water overlying a turbidity current is stagnant, and therefore it cannot take up or hold sediment in suspension. Hence no sediment is dissipated outside the turbidity current itself. In-mixing of clear water into the current can dilute the suspension, but without decreasing the total amount of the load. Hence the potential energy, which depends on load combined with difference in level, remains the same, though the mass to be moved increases and therefore the velocity diminishes.

In a river the water is turbulent throughout, and the sediment becomes distributed over the entire thickness, an upward decrease in concentration balancing the settling velocity for each grain size.

Smaller slump structures are often found associated with series of graded graywackes. Even more common are shale inclusions in certain graywacke beds, in swarms or separate. Such graywacke beds with inclusions may show absence of grading or other features indicating that the slump, which created the turbidity current from which they settled, took place close at hand.

In the experiments a transitional type of movement between turbidity flow and slumping was observed. Part of the suspension, when densities of 1.5 or higher were used, shot along the bottom over a distance of some metres in a thin wedge lagging only slightly behind the nose of the overlying turbidity current. It formed an unsorted deposit of the composition of the suspension. The high velocity suggests a low viscosity, the shape and the sharp boundary with the turbidity current argue for a non-turbulent type of flow. To this uncertainty concerning the nature of the flow must be added that it is doubtful whether it occurs under natural conditions.

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In conclusion, the main differences between sliding and turbidity flow are summarized in the following table.

Submarine slide

Movement : Sliding, more or less turbulence, cracks forming. Highest speed at surface, but not much variation throughout the mass. Sharp transition to clear stagnant water above. Halts suddenly, entire bulk stopping at same moment. No subsequent change, no segregation of larger particles. Requires slope of 1° or more, cannot continue on horizontal floor.

Deposit : Usually fair proportion of lutite, may contain huge blocks. Original structure slightly deformed to entirely mixed. One or more strata involved. Piling up at lower end, stretching at higher end.

Turbidity current

Movement : Turbulent throughout. Speed decreasing from near bottom to surface, and from nose to rear. Transition to stagnant overlying water via dilute suspension in slow boiling movement. Deposition starts where slope decreases, continues normally as long as flow moves. At each point : sedimentation during passage of flow, hence finished earlier closer to the origin. Current can move far on horizontal floor.

Deposit : More or less distinctly graded granular bed, poorly sorted (= dirty) in each level. Coarsest grains do not exceed 10 cm. Upper part may be laminated, and current ripple laminated. One current produces one single bed.

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REFERENCES

- ERICSON, D. B., EWING, M. and HEEZEN, B. C. (1952), Turbidity currents and sediments in North Atlantic. *Bull. Am. Ass. Petr. Geol.*, Vol. 36, pp. 489-511.
- FAIRBRIDGE, R. W. (1946), Submarine slumping and location of oil bodies. *Bull. Am. Ass. Petr. Geol.*, Vol. 30, pp. 84-92.
- HEEZEN, B. C., ERICSON, D. B. and EWING, M. (1954), Further evidence for a turbidity current following the 1929 Grand Banks earthquake. *Deep-Sea Res.*, Vol. 1, pp. 193-202.
- HEEZEN, B. C. and EWING, M. (1952), Turbidity currents and submarine slumps and the 1929 Grand Banks earthquake. *Amer. J. Sci.*, Vol. 250, pp. 849-873.
- JONES, O. T. (1947), The geology of the Silurian rocks West and South of the Carneddau Range, Radnorshire. *Quart. J. Geol. Soc. London*, Vol. 103, pp. 1-36.
- KUENEN, Ph.H. (1948), Slumping in the Carboniferous of Pembrokehire. *Quart. J. Geol. Soc. London*, Vol. 104, pp. 365-385.
- KUENEN, Ph.H. (1951), Properties of turbidity currents of high density. *Soc. Econ. Pal. Min.*, Sp. Publ. 2, Turbidity Currents, pp. 14-33.
- KUENEN, Ph.H. (1952), Estimated size of the Grand Banks turbidity current. *Amer. J. Sci.*, Vol. 250, pp. 874-884.
- KUENEN, Ph.H. (1953), Significant features of graded bedding. *Bull. Amer. Ass. Petr. Geol.*, Vol. 37, pp. 1044-1066.
- KUENEN, Ph.H. and MENARD, H. W. (1952), Turbidity currents, graded and non-graded deposits. *J. Sed. Petr.*, Vol. 22, pp. 83-96.
- KUENEN, Ph.H. and MIGLIORINI, C. I. (1950), Turbidity currents as a cause of graded bedding. *J. Geol.*, Vol. 58, pp. 91-127.
- MENARD, H. W. (1955), Deep-sea channels, topography and sedimentation. *Bull. Amer. Ass. Petr. Geol.*, Vol. 39, pp. 236-255.

A comparison of methods for forecasting wave generation[‡]

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Abstract—Wave heights and periods in the generating areas of an unusually severe storm and its forerunner were hindcast by three different methods and compared with observations. Wave height agreement was good for all methods. Period agreement was poor; however, all reported periods fell within the spectral range determined by the Pierson-Neumann-James method. The description of a sea in terms of its spectrum is indicated.

DURING the last war a method was developed by SVERDRUP and MUNK (SVERDRUP and MUNK 1947, U.S. Navy Hydrographic Office 1951) for forecasting the heights and periods of wind waves at sea from a knowledge of the wind velocity, its duration and the fetch over which it blew. On the basis of additional data, these relationships were later modified by BRETSCHNEIDER (1952a, b). In both methods the resulting waves were described by a "significant wave height," and a "significant period" defined as the average height and period of the one-third highest waves. More recently, a number of papers (JAMES, 1954; NEUMANN, 1953; PIERSON, NEUMANN and JAMES, 1954) have given a method for forecasting ocean waves by means of wave spectra and statistics. Results of LONGUET-HIGGINS (1952) enable calculation of a "significant height" from the derived energy spectrum for comparison with results from other methods. An average "period" of all the waves with crests above and troughs below mean sea level can also be obtained, which, although it has a somewhat different definition than the "significant period", can be expected to have a similar value.

At present there is a shortage of good observational data with which to compare these forecasting methods under various conditions. It is necessary that comparisons be made in both the generating and decay areas to verify the particular relations applicable to each case. Ideally, the generating area should be studied first, but unfortunately this is generally not the case since waves, especially the larger ones, are most often observed after they have left their generating area. In an investigation of the storm responsible for the loss of the S.S. *Pennsylvania* with all hands on January 9, 1952, at approximately 51°N 141°W, it became apparent that this storm could be used to give excellent comparisons between the different methods for forecasting wave generation in a range of wave heights seldom encountered (up to 48 feet or 14.6 metres). Conditions were extremely favourable for an accurate forecast; waves were observed by trained, experienced observers at two weather ships in the generating area; the wind remained between 45 and 55 knots (23.2 and 28.3 metres per second) for 33 hours, with 18 consecutive hours of winds over 50 knots (25.8 metres per second); the wind was relatively uniform over a 500-mile (927 kilometres) fetch; accurate anemometer wind observations were obtained from the two weather observa-

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tion ships, the Canadian Weather Ship *Stonetown* occupying Station Papa at 50°N 145°W, and the USCGC *Wachussetts* en route to Station Sugar at 48°N 162°E. Figure 1 shows the storm at the height of its intensity, and includes the location of all weather reporting ships in the area. In particular, notice the favourable position of the USCGC *Wachussetts*, which has just passed through the upwind end of the storm area responsible for the large waves observed at the *Stonetown*.

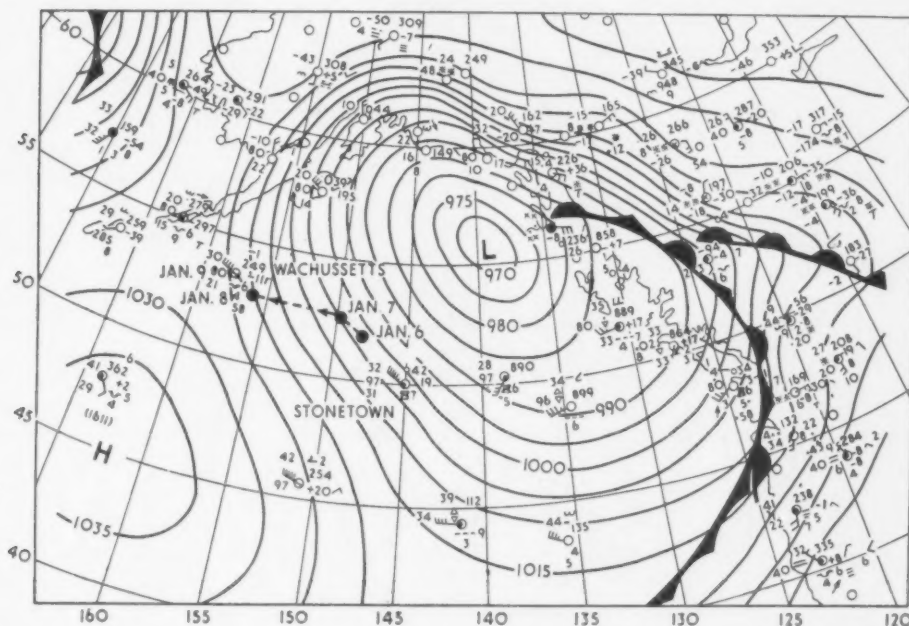


Fig. 1. Northeast Pacific weather map for 1230 Jan. 9, 1952. Noon positions of USCGC *Wachussetts* are shown for Jan. 6, 7, 8 and 9.

This storm was unique in its wave-making ability. A survey of the historical weather maps back to 1922 (U.S. Weather Bureau) showed only one other storm in the Gulf of Alaska capable of maintaining waves of this size for such an extended period of time. Several features combined to create the unusual situation: the track of the storm as it entered the Gulf of Alaska was such that its generating area started at the upwind end of the final fetch, and moved in the wind direction; it intensified in such a position (Fig. 1) that it drew in an unusually cold air mass from the interior of Alaska, causing a flow of very unstable air over the fetch with a maximum sea-air temperature difference at Station Papa of 12°F (6.7°C); and, as the storm intensified, it stagnated, permitting this maximum wind to remain over the same fetch.

Wave heights and periods for this storm and its forerunner were calculated independently by the two authors using the Sverdrup-Munk, Bretschneider and Pierson-Neumann-James methods. Synoptic weather maps (U.S. Weather Bureau 1952) for every 6-hour interval were split into regions of different wind velocities, and then a stepwise process used to determine the wave characteristics over the whole fetch at the end of each six hours. The results are shown together with the Station Papa wave and wind observations in Fig. 2.

The overall agreement on wave heights is good. The Sverdrup-Munk, and Bretschneider results are for all practical purposes identical, and are shown by the same curves. They give excellent agreement with the observed values. The small differences can easily be explained by the averaging processes necessarily used to represent the actual wind field. The Pierson-Neumann-James method seems to

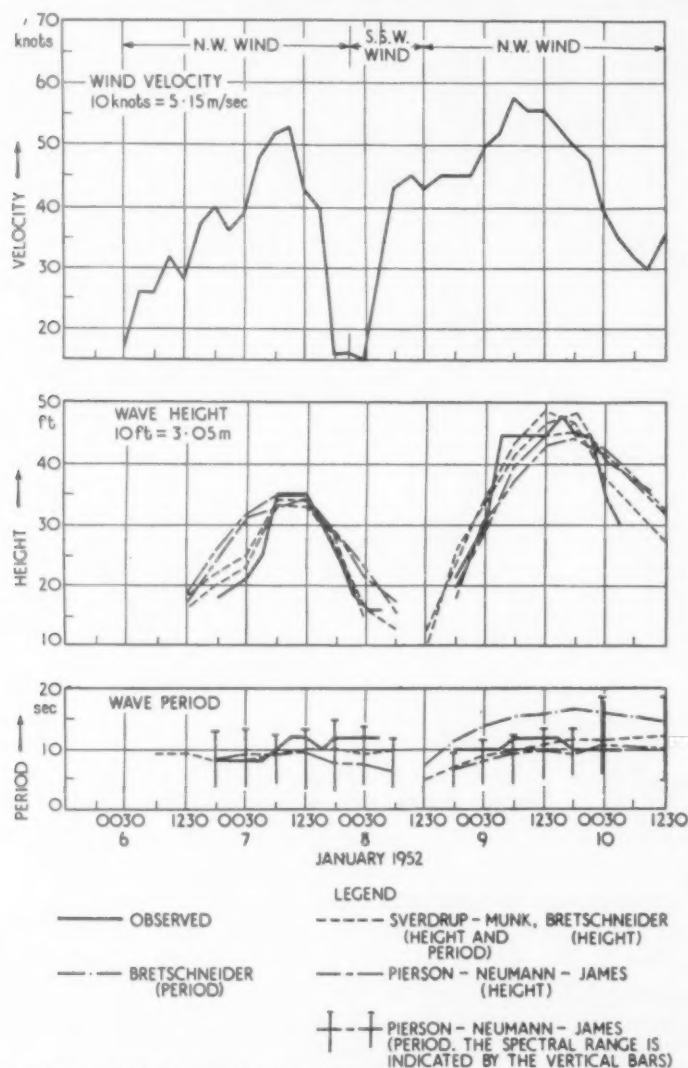


Fig. 2. Comparison of hindcast and observed waves at Ocean Station Papa (50°N., 145°W.).

give some characteristic differences from these particular observations. With wind speeds in the range 30-40 knots, this method gives a faster build-up of wave height than that observed. This is shown from 1230 January 6, to 0030 January 7, while with higher wind speeds it gives a slower build-up as shown, 0030 January 7 to

0630 January 7, and 0030 January 9 to 1230 January 9. The decay calculated by the use of Filter IV modified for gradual decrease of wind and the angular spreading factor agrees quite favourably with the observations and the Sverdrup-Munk theory in the first storm, but not quite so well in the second. In the first storm, Station Papa was near to the edge of the fetch, which accounted for the more rapid decay. The weather ship ceased taking three-hourly wave observations at 0330 on January 10 due to the necessity of carrying out rescue operations, and thus further decay cannot be compared for this storm.

The agreement between calculated and observed periods is not particularly good. The Sverdrup-Munk values give best agreement, generally within ± 2 seconds, but their variation from the observed values follows no fixed pattern. The Bretschneider values are consistently about 60% higher than those given by Sverdrup-Munk. The Pierson-Neumann-James average "periods" are generally comparable, but somewhat less than the Sverdrup-Munk "significant periods" as might be expected. In all cases the observed "significant period" fell within the spectral range of periods given by their method.

This comparison between wave-forecasting methods shows that in the generating area either the Sverdrup-Munk or Bretschneider results gives a result closely comparable to this set of observations. With a knowledge of the "significant height" most other height data can be calculated. The Pierson-Neumann-James heights are also good, but are not in as close agreement with this set of observations as the forecast heights obtained by the other two methods. The overall agreement on periods is not very good. The Sverdrup-Munk theory gives a rough agreement which is satisfactory for some purposes, but in order to describe the sea more completely, it is evidently necessary to obtain information on its spectrum. Unfortunately observational data available were not suited to determine the applicability of the Pierson-Neumann-James procedure in this regard.

ACKNOWLEDGEMENTS

Attention was drawn to this storm by Messrs. STANLEY B. LONG, C. CALVERT KNUDSEN and EDWARD C. BIELE of Bogle, Bogle and Gates in connection with the loss of the S.S. *Pennsylvania*. The investigation of the wave characteristics in the storm by use of H. O. Publ. No. 604 was supported by Bogle, Bogle and Gates. The meteorological features of the investigation used in this paper were obtained from Dr. ROBERT G. FLEAGLE and Mr. EDWIN F. DANIELSON.

REFERENCES

- BRETSCHNEIDER, C. L. (1952a), The generation and decay of wind waves in deep water. *Trans. Amer. Geophys. Union*, **33** (3), 381-389.
- BRETSCHNEIDER, C. L. (1952b), Revised wave forecasting relationships. *Proc. Second Conf., Coastal Engineering*, 1-5.
- JAMES, R. W. (1954), An example of a wave forecast based on energy spectrum methods. *Trans. Amer. Geophys. Union*, **35** (1), 153-160.
- LONGUET-HIGGINS, M. S. (1952), On the statistical distribution of the heights of sea waves. *J. Mar. Res.*, **11** (3), 245-266.
- NEUMANN, GERHARD (1953), On ocean wave spectra and a new method of forecasting wind-generated sea. *Beach Erosion Board, Tech. Mem. No. 43*, 42 pp.
- PIERSON, W. J. Jr., NEUMANN, GERHARD and JAMES, R. W. (1954), Practical methods for observing and forecasting ocean waves by means of wave spectra and statistics. New York University, College of Engineering, Res. Div., 322 pp.

- SVERDRUP, H. U. and MUNK, W. H. (1947), Wind, sea and swell : theory of relations for forecasting. *H. O. Pub.* No. 601, 44 pp.
- U.S. Navy Hydrographic Office (1951), Techniques for forecasting wind waves and swell. *H. O. Pub.* No. 604, 38 pp.
- U.S. Weather Bureau (1952), Synoptic Weather Maps for January, 1952, Seattle, Washington.
- U.S. Weather Bureau, Historical Weather Maps, Daily Synoptic Series, Northern Hemisphere, Sea Level, Washington, D.C.

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Survey of a seapeak in the Mozambique Channel*

Acting Commander J. T. K. PAISLEY, Royal Navy

(Received 18 May 1955)

THE current practice for all H.M. Surveying Ships making a passage from one port to another is to plan the passage so that, without deviating too much from the direct route, the ship shall pass through any areas which appear to be little known. A continuous record of soundings is maintained, and other oceanographical observations are also obtained. In this way a considerable body of information is being built up, and Admiralty charts are continually being improved by the addition of the information so obtained. Much of this information is of comparatively little interest to the surface navigator, and is therefore only incorporated in the charts when new editions are being prepared, or when the accumulation of information in any area justifies a large correction. Occasionally, however, a new and prominent submarine feature is discovered which can be of great value to the mariner in assisting him to confirm his dead reckoning when out of sight of land, and such a feature will be embodied in the charts immediately by means of a block correction.

A case in point is the discovery of a previously unknown seapeak in the Mozambique Channel by H.M.S. "Dalrymple" while on passage from Durban to Mombasa in September, 1954. Referring to the reproduction of a portion of Admiralty chart No. 2762, as it was at that date (Fig. 1), it will be seen that between the latitudes of 13° South and 15° South there is a blank area lying between two lines of soundings which run 355°-175°, and which cross the parallel of 14° South in 41° 18' East and 41° 46' East approximately. H.M.S. "Dalrymple's" designed track was laid down to bisect this 28 mile wide blank area.

At 0700 on the morning of the 28th September the ship was in approximate position 14° 18' South, 40° 30' East (i.e. about 3 miles to port of the designed track), in 1,209 fathoms of water and steering a course to make good 355°. Soundings began to shoal noticeably at about 0720, the 1,000 fathom line was crossed at 0734, and at 0752 a peak sounding of 252 fathoms was recorded. There was thus a rise in the sea bed of some 5,700 feet in a horizontal distance of just over 5 nautical miles.

It was at once decided that this feature, provisionally classed as a seahigh, merited a full investigation, and the passage was broken off. While a beacon was being rigged the ship returned and, running lines about half a mile apart parallel to the original course, by dead reckoning, endeavoured to obtain a preliminary picture of the top of the feature. Purely by good luck the initial turn was made in the right direction, and the probable highest point was soon found. The least water recorded during this preliminary stage was 168 fathoms.

The beacon, which was fitted with two radar reflectors, was laid in 180 fathoms of water with 300 fathoms of mooring. In theory it was thus free to move anywhere within a circle of about two cables radius, but in practice it always lay well out to a

* Published by permission of the Admiralty.

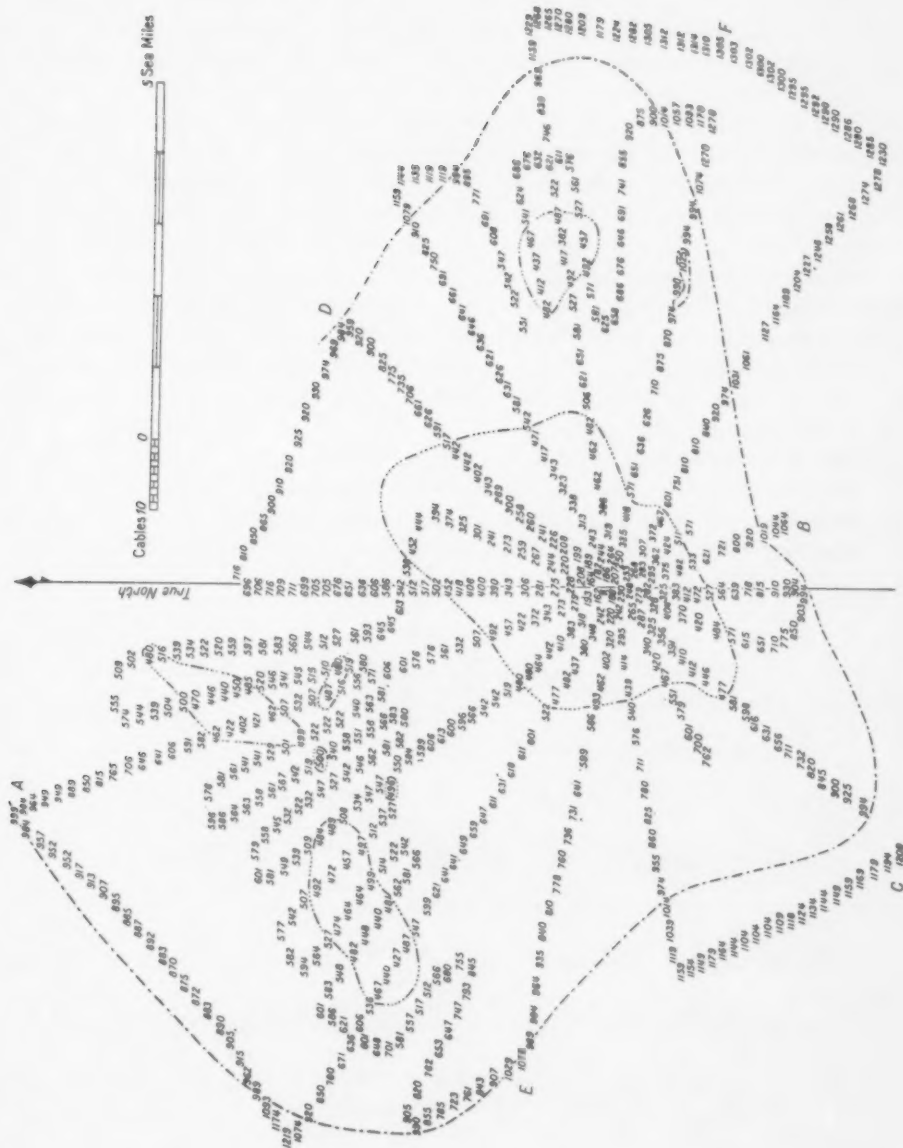


Fig. 2. Selection of Soundings.

strong (2 knot) southerly current, and maintained a very steady position. The same sounding was recorded time after time as the ship subsequently steamed close by while sounding.

The scale selected for the investigation was 1/72,000. This was large enough to ensure that the main features of the seahigh could be accurately delineated, and small enough to ensure that the whole could be plotted on a conveniently sized sheet; a very convenient scale on which to work, as one "radar-mile" of 2,000 yards corresponds to one inch on paper.

After allowing half an hour for the beacon to settle, sounding was started and was continued until dusk, when the ship was stopped about a couple of miles away from the beacon to enable evening star sights to be observed. By remaining well away from the beacon, an accurate fix relative to it can be obtained by radar as each star is observed. This method is preferred to heaving to in the immediate vicinity of the beacon and estimating one's distance from it, as it permits the ship to remain on a constant heading throughout. Morning stars were similarly observed the next morning, and sights of the sun and Venus were observed while sounding the following day. All the position lines thus obtained were used to derive the position of the beacon, which was accepted as $14^{\circ} 10' \cdot 7$ South, $41^{\circ} 28' \cdot 7$ East.

The sounding plan was as follows:—

- (i) lines to be run radially from the beacon.
- (ii) lines 20° apart to be extended to the 500 fathom line.
- (iii) lines 40° apart to be extended to the 1,000 fathom line.
- (iv) interlines and cross-lines to be run as found necessary as a result of (ii) and (iii).

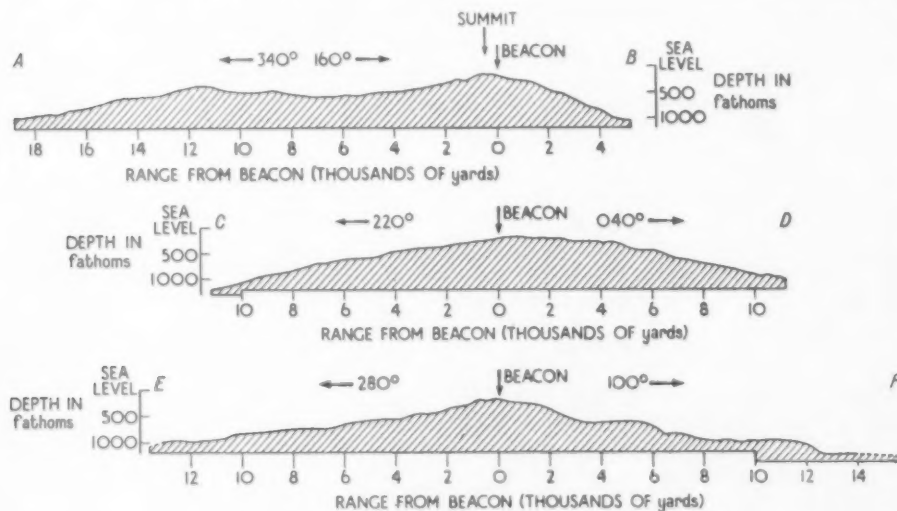


Fig. 3. Profiles of Seapeak.

In the event, interlines were run 5° apart to delineate isolated peaks under 500 fathoms in depth, and the soundings were not carried sufficiently far out to cover the 1,000 fathom line to the north of the seahigh.

While sounding, the ship recorded the depth of water every 30 seconds, and fixed

her position every three minutes by gyro compass bearings and radar ranges of the beacon. Fig. 2 shows a selection of the soundings obtained, on a scale somewhat reduced compared with that of the original survey. They have been corrected for the speed of sound in sea water as given in Admiralty publication No. H.D. 282 ("Tables of the Velocity of Sound in Pure Water and Sea Water for use in Echo-Sounding and Sound-Ranging." (D. J. Matthews) 2nd. Edition 1939). Profiles of the feature on three equally spaced bearings have been drawn and are shown in Fig. 3. In this drawing the horizontal and vertical scales are the same (7,200 feet to 1 inch).

From these two figures, and taking into consideration also the other charted depths in the vicinity, it would appear that the comparative isolation of this seahigh from the continental shelf can be accepted. If this is so, then it clearly falls within the classification of seamount, i.e. "an isolated or comparatively isolated elevation of the deep-sea floor of approximately 3,000 feet or more." The actual summit is fairly flat (an area of approximately 450 yards by 150 yards has less than 50 feet variation in height), but this area is so small in relation to the whole that it can certainly be regarded as having "a pointed top." As it is also "roughly circular or elliptical in plan" it should be placed in the more restricted category of seapeak. The name "Paisley Seapeak" has been approved by the British National Committee on the Nomenclature of the Bottom Features.

Sounding was completed at 1600 on the second day, September 29th, and the ship then went into deep water at the edge of the seapeak to obtain a sample of the bottom. A fair sample, of Mud and Sand, was obtained in position $141^{\circ} - 8,000$ yards from the beacon, in approximately 1,200 fathoms, using a Baillie rod. The ship then returned to the top of the seapeak to get another sample there. As we hoped for a bigger sample, a bottom dredge was first used, but after three abortive attempts this was abandoned and the Baillie rod was again sent down. The first cast again produced nothing, but the second brought up a small chip of granitic rock*. As the Baillie rod will not normally obtain a sample from a rocky bottom this was regarded as a stroke of luck unlikely to be repeated, and no further attempts were made.

As the investigation was now reasonably complete, and as the ship was getting very short of fuel, the beacon was weighed and the ship resumed her passage to Mombasa. Had circumstances permitted, it would have been desirable to complete the delineation of the 1,000 fathom line to the north and north-east of the seapeak, and also to obtain further bottom samples from the slopes of the seapeak.

Another point of interest would be to establish whether there is any connection between this seapeak and the 850 fathom sounding charted some 27 miles N.N.W. of it, and between this and the 890 fathom sounding charted some 32 miles further N.N.W. The natures of the bottom charted at these two points make it appear unlikely, but the fact that they *are* shoal soundings, and that they lie so nearly in a straight line, is at least suggestive of the existence of a submarine mountain range. Even were the existence of such a range proved, it would still appear to be completely detached from the continental shelf, as a sounding of 1,100 fathoms lies on the extension of this N.N.W'ly. line, and between the further shoal sounding and the mainland.

*This has now been analysed by the British Museum of Natural History and found to be a type of lava.

LETTERS TO THE EDITORS

Leeuwin Sill

Abstract—The evidence for the Leeuwin Sill, a name proposed by CARRIGY and FAIRBRIDGE (1954, p. 83) and FAIRBRIDGE (1955, p. 162) is reviewed. Soundings from this area reported to the International Hydrographic Bureau give no evidence for a sill with a depth of under 2,000 fms extending southwards from Cape Leeuwin for some 200 miles.

In an article "Some bathymetric and geotectonic features of the eastern part of the Indian Ocean" by FAIRBRIDGE (1955) under the heading "New Features Designated" is included Leeuwin Sill. The latter, is described as "a low ridge of under 2,000 fathoms depth, connecting the south-western point of Australia, Cape Leeuwin, with the South-West Australian Ridge (of VENING MEINESZ, 1948)" and it is stated that "it trends roughly North and South and is about 200 miles long."

An editorial note inserted at the end of this article states that the British National Committee on the Nomenclature of Ocean Bottom Features which met on 26th November, 1954 "came to the conclusion that the names Leeuwin Sill would require further consideration."

At a meeting of the International Committee on the Nomenclature of Ocean Bottom Features which was held at the headquarters of the International Hydrographic Bureau (hereafter referred to as the I.H.B.) in Monaco on 9-10 September, 1954, during which meeting the delegates had carefully examined the plotting sheets of oceanic soundings used by the I.H.B. for the preparation of the Third Edition of the General Bathymetric Chart of the Oceans, the Chairman stated that he was of the opinion that the sill (Leeuwin Sill/Rise) was a misnomer as there was considerable doubt of its existence. It was agreed that the I.H.B. should look into the matter.

This question has since been given very careful consideration by the I.H.B. and the following remarks are offered :—

- (a) It should be noted that the I.H.B. has since 1929 been entrusted with the collation of information concerning all soundings taken outside the continental shelves, and with the keeping up to date of the General Bathymetric Chart of the Oceans of which the "Cabinet Scientifique du Prince Albert de Monaco" had drawn up the first and second editions.
- (b) A new edition of Sheet A'III of the General Bathymetric Chart, which covers the area in question, was issued in 1942 and contains a selection from all soundings received in the I.H.B. up to that year*. If however VENING MEINESZ received additional information between that date and 1948 for the preparation of the chart accompanying his work "*Gravity Expeditions at Sea. 1923-38*," referred to in the above mentioned article, such information has not been received in the I.H.B.

Leeuwin Sill is not shown on Sheet A'III of the General Bathymetric Chart of the Oceans.

- (c) It is noted that on SCHOTT's (1935) chart, this sill is also not shown, the single unbroken South Australian Basin (over 5,000 m) extending from Longitude 111° East, South-westward from Cape Leeuwin, to 141° East.

The attached figure shows a selection from all the available soundings (in fathoms) used for Sheet A'III mentioned in (b). The I.H.B. has received no soundings in the area between that of 1,776 fathoms shown seventy five miles to the southward of Cape Leeuwin and the 2,487 fathoms, one hundred and fifty miles southward of the Cape, and we therefore have no knowledge as to how much further to the southward the 2,000 fathom line may extend than is shown. The available soundings do however tend to disprove the statement that "Leeuwin Sill is about 200 miles long."

From the above it will be seen that no evidence supporting the existence of Leeuwin Sill has been received by the I.H.B., but that on the contrary the soundings plotted indicate an unbroken area of over 2,000 fathoms extending in an east-west direction 130 miles, and may be at a lesser distance, to the southward of Cape Leeuwin, as is already shown on SCHOTT's (1935) chart.

* See I.H.B. Special Publication No. 30—Part A'III "Information concerning the preparation of the Third Edition of Sheet A'III of the G.B.C."

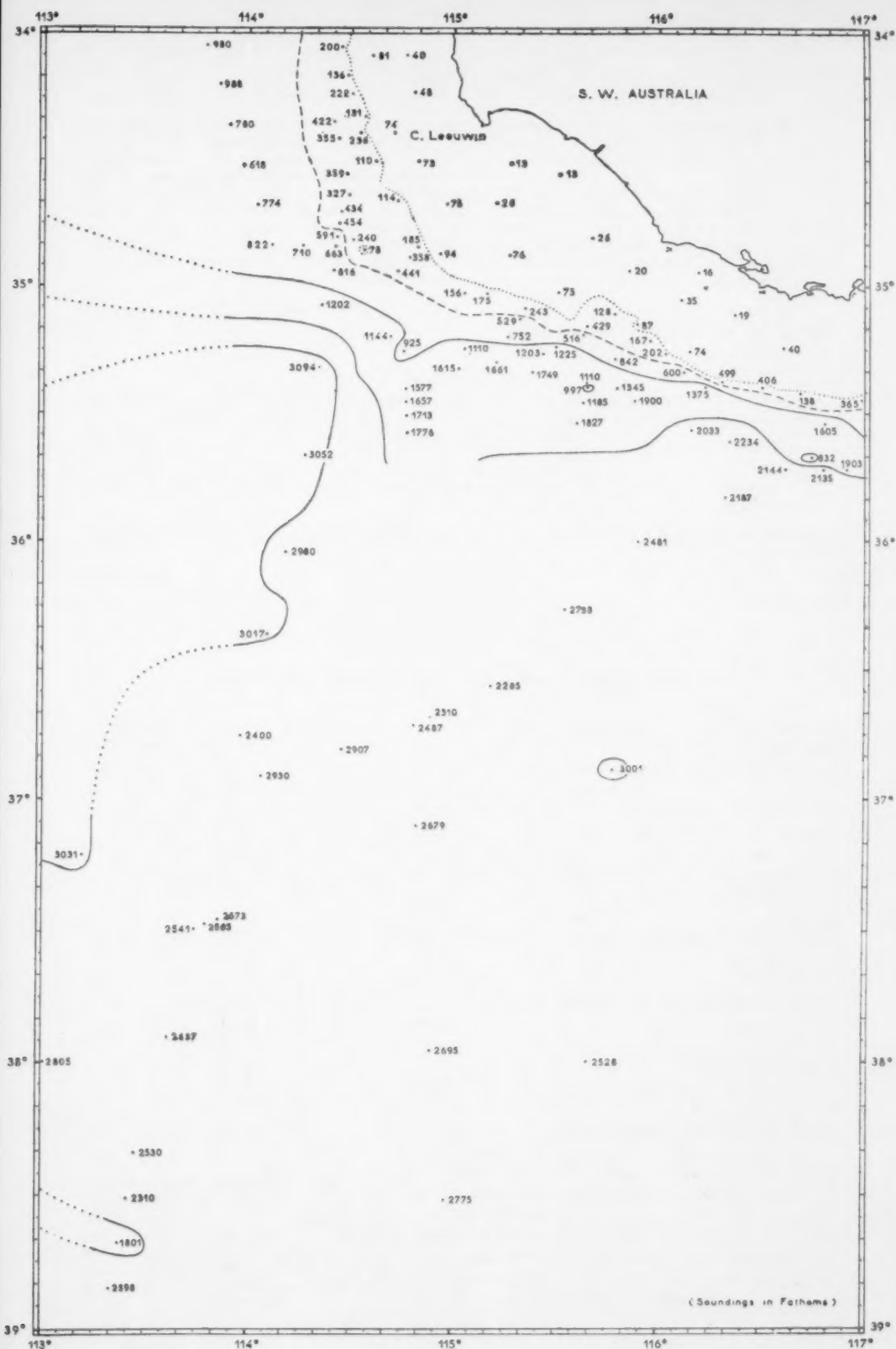


Fig. 1. Soundings in the vicinity of Leeuwin Sill mentioned in *Deep-Sea Research* (1955) 2, 162 used for the preparation of Sheet A'III of the General Bathymetric Chart of the Oceans. (Soundings in Fathoms).

For the information of readers of *Deep-Sea Research* it is pointed out that, in preparing the new sheets of the General Bathymetric Chart of the Oceans, all available soundings are first plotted on a series of sheets 10 times the scale of the finished chart* and the contours are drawn accordingly; they are then adjusted to agree so far as possible with those shown on maps accompanying various reports of scientific expeditions, etc., received in the bureau. A selection from the soundings is then made on tracing paper and these are reduced by photography to the required scale and sent to the printers for the preparation of the published chart. It is the bureau's present practice to send a copy of the first proof, whenever possible, to an outside specialist for his criticism and any suggested amendments. It is therefore hoped that the final sheets published will meet the needs not only of hydrographers but of all scientists interested in deep-sea research.

VICE ADMIRAL J. D. NARES, D.S.O.

International Hydrographic Bureau, Monaco.

REFERENCES

- CARRIGY, M. A. and FAIRBRIDGE, R. W. (1954), Recent sedimentation, physiography and structure of the continental shelves of Western Australia - *J. Roy. Soc. West. Austral.*, **38**, 65-95.
 FAIRBRIDGE, R. W. (1955), Some bathymetric and geotectonic features of the eastern part of the Indian Ocean. *Deep-Sea Res.*, **2**, 161-171.
 SCHOTT, G. (1935), *Geographie des Indischen und Stillen Ozeans*. Hamburg (Boysen), 413.
 VENING MEINESZ, F. A. (1948), Gravity Expeditions at sea 1923 - 1938, *4, Publ. Netherlands Geodetic Comm.*, 1-233.

* Except in the vicinity of the Poles where the plotting sheets are 5 times that of the finished chart.

An oceanographical curiosity : the perpetual salt fountain

In many tropical and subtropical regions of the ocean the warm surface layers have a salinity exceeding that found in the colder waters of polar origin below. If a long tube were lowered from the surface to depth of low salinity water, and the deep water were slowly pumped to the surface through the tube, and the pump then disconnected, the water would continue to flow, by itself, forever. This remarkable phenomenon occurs because slow motion through the tube allows the water inside to attain the same temperature as the surrounding water. Its salinity, and hence density, is therefore less than that of its surroundings outside the tube, and hence the entire column of water inside the tube is buoyant with respect to the fluid outside at the same level. If the direction of pumping is reversed, so that the fluid initially goes downward, it will of course continue to flow downward forever on account of its excess in density over that of the water outside the tube.

Although the attempt has not been made it is likely that in the Central North Atlantic with a tube 2,000 meters long, one might develop a pressure head of as much as two meters at the surface. A simple experiment on a laboratory scale will demonstrate the principle, however. A vertical glass tube, about three inches in diameter (A in Fig. 1) is filled halfway with hot fresh water. Then the same quantity of slightly coloured cold fresh water is introduced through a hole in the bottom (B) care being taken not to produce too much mixing at the interface between the two fluids. An

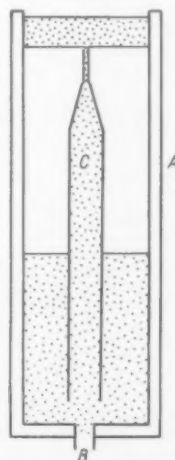


Fig. 1. Laboratory experiment to demonstrate the salt fountain, showing outside glass tube A, with hole in the bottom for filling B, and inner glass tube C to produce the fountain. The shading indicates the coloured water after the fountain has been in operation for some time.

inner tube, C, slightly restricted at the top to suppress secondary flows that tend to develop inside it, is now gently lowered into the fluid. The operator keeps his finger over the upper end until the lower end is below the interface so as to fill the inner tube entirely with the lower fluid. If this is done slowly enough so that the coloured water in the inner tube equalizes temperature with the fluid outside at the same level, it will stay above the outside interface even after the top of the tube C is below the surface of the upper layer. After the system has stood for a few minutes there will be evidence of small secondary motions and circulations inside tube C, but these appear to be associated with the slow cooling and warming of the system as a whole. Up until this stage of the demonstration there has been no salinity difference involved. Now we add with gentle stirring a little hot salt water to the upper layer outside tube C, but not enough to upset the overall stability of the two layered system outside tube C. Immediately a strong jet of coloured bottom water starts to flow from the nozzle at the top of tube C. A third layer – fresh, warm and coloured – forms at the very top. The flow continues until the conditions of the experiment break down. In the ocean, however, the stratification is maintained by large scale climatological influences, and the tube could have no reaction upon the external situation, so that it would flow forever.

It seems premature to speculate upon the improbable practical importance of this phenomenon for pumping up nutrient rich deep water to the surface for fish-farming applications, or its inverse for removing waste products to the deep water. As a power source it is quite unpromising. Thus it remains essentially a curiosity.

HENRY STOMMEL
ARNOLD B. ARONS
DUNCAN BLANCHARD

Contribution No. 799 of The Woods Hole Oceanographic Institution, Woods Hole, Mass., U.S.A.

Evidence for echolocation by cetaceans

(Received 24 October 1955)

[THE late ARTHUR F. MCBRIDE worked many years at Marine Studios, Marineland, Florida, where he was Curator. It is very largely due to his efforts and devotion that it is now comparatively easy to keep small cetaceans captive in good health and well being (the porpoises on exhibition at Marine Studios have gone into the third generation). Not only did ARTHUR MCBRIDE successfully overcome the manifold difficulties at first encountered, but since he was an excellent and objective observer, he also made many significant contributions to the biology of the delphinids. A few of these he published, but unfortunately his modesty led him to withhold a number of them, evidently feeling that they should be checked and polished.

In 1947 he and Dr. D. O. HEBB, who was then at Harvard University, prepared their joint paper on the behaviour of captive *Tursiops* (*J. Comp. Physiol. Psychol.*, 41 (2), 111-123, April 1948), in which were utilized only some of the notes assembled by MCBRIDE. By the courtesy of Marine Studios I was permitted to make extracts from the unpublished material, and with the cordial concurrence of Dr. HEBB I offer this to show that as long ago as 1947 Mr. MCBRIDE had noted some solid evidence that porpoises must be using sound for navigation. This was before any other workers had done more than surmise that this might be so, and it is in the hope that Mr. MCBRIDE's priority in this matter may be recognized that the following extract from his notes is offered.

At this laboratory we have in hand acoustic measurements of such nets in the hope of throwing some light on this problem; we have also during the past summer enlisted the aid of a porpoise in this work. This porpoise and those observed by MCBRIDE were *Tursiops truncatus* (Montagu).]

WILLIAM E. SCHEVILL

Woods Hole Oceanographic Institution.

ONE of our fishermen who has worked for us since 1939 and who has probably caught more porpoises than anyone living, has stated that a porpoise will not charge into an ordinary seine such as is used

for catching mullets and other small fishes. Instead the porpoises will jump over the cork line to escape. We use heavy nets with a mesh about 10 inches square for capturing porpoises, and my informant says that the animals will invariably charge such a net and of course are readily caught. He further states that the only time one jumps over this type of net is after the others have struck it and have momentarily pulled the cork line under the water. This man is unusually reliable and I have full confidence that his observation is basically sound.* I have seen his latter observation borne out on at least three occasions, but have never personally observed the porpoises' behaviour regarding the small meshed seine.

Two points seem to be significant. The porpoises recognized the fine mesh net from the coarser under conditions which make the operating of visual sense improbable. The waters in which this occurs are extremely turbid and the animals are usually caught at night. The possibility of phosphorescence from planktonic organisms has not been eliminated, although such phosphorescence is not visible to a human eye above the surface. The second point is that when the cork line of the net is pulled under the water, a porpoise not already caught in the net recognizes that what was formerly a solid barrier now has an opening. He promptly rolls over the net where the cork line is lowest. On one of the occasions I have observed this, the night was pitch dark and the porpoise who escaped was not swimming close to the net. He streaked for the low spot in a flash, rolled over it and was gone.

This behaviour calls to mind the sonic sending and receiving apparatus which enables the bat to avoid obstacles in the dark. In view of the enormous development of the cerebral cortex of the porpoise and its probable dependence on the penetration of large numbers of sensory impulses into this region and the formation of correlation centres there (LANGWORTHY†), and because of the obvious importance of the acoustic sense to the porpoise, might we not suspect that the above described behaviour is associated with some highly specialized mechanism enabling the porpoise to learn a great deal about his environment through sound?

ARTHUR F. MCBRIDE

Marine Studios

2 July 1947

* This fisherman is undoubtedly RONALD V. CAPO, and I can strongly confirm the statement that this man is unusually reliable.—W.E.S.

† 1932, *J. Comp. Neur.*, 54 (2), 437-499.—W.E.S.

BOOK REVIEWS

The Meteorology of the Falkland Islands and Dependencies, 1944-1950. J. PEPPER. pp. 249. 42s. Meteorological Office, London.

Annual Meteorological Tables, 1951-1953. 10/- per volume. Falkland Islands and Dependencies Meteorological Service. Stanley, Falkland Islands.

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THE Falkland Islands with their sub-Antarctic and Antarctic dependencies might be described as a paradise for inhuman research, and not least in the realm of meteorology. Fully exposed to the vicissitudes arising from the constant procession of frontal lows, characteristic of the higher southern latitudes, they are at the same time much affected by variations in the extent of sea-ice, and by a diversity of local factors especially around the mountainous coasts of Graham Land. Further excitement arises from their location on either side of the Antarctic Convergence, that curiously significant marine boundary north of which the earth again smells of growing things ; whereas on the poleward side, South Georgia in the latitude of Slesvig resembles Jan Mayen. A region which, according to recent studies, provides little or no abiding-place for " blocking highs " ; in which, thanks to this Service, we are beginning to know the characteristics of the upper flow ; a region with quaint climatological curiosities, such as the potential occurrence of the highest temperature of the year in mid-winter.

The work under notice is a first-class scientific accomplishment. It bears the stamp of accurate and reliable observation, sober compilation and convenient statistical assemblage, presenting a very thorough resumé of the results of meteorological observation at the ten bases operated by the Falkland Islands Dependencies Survey, which is likely to prove welcome to scientists of all nations. The Meteorological Service thus set up provides an unusually valuable basis not only for research, but also for the very practical need to provide a forecasting service for whalers and other vessels operating in these stormy waters. Moreover, as H. H. LAMB has shown, the relatively regular behaviour of the atmosphere over the Southern Ocean means that the F.I.D.S. reports cannot be dispensed with even when the forecaster is 180° distant in longitude ; and they appear to give some promise of a basis for more extended forecasts. The provision of a statement of the meteorological characteristics of the several F.I.D.S. reporting stations, from Stanley and South Georgia to Marguerite Bay in Graham Land beyond 68°S., and of frequencies, averages and extremes so far recorded, is thus very welcome ; and Dr. PEPPER of the Meteorological Office is to be congratulated on his comprehensive and workmanlike study.

The first section is devoted to a discussion of the observations. Maps and diagrams abound ; particular note can be taken of a complete range of mean monthly isobars (pp. 18-19) covering the whole region, and of a very fine set of wind roses (pp. 36-42). It is a little surprising to find that seven years' observations show that the latitudinal location of the axis of lowest pressure lies south of the tip of the Graham Land peninsula in all months except January, and lies furthest south in late winter ; and inverse movement to that which might initially be thought to prevail. Local characteristics of the stations and the effects of presence or absence of sea-ice are admirably outlined. Details of stations are supplemented with photographs and maps of the locality ; in some instances a scale would be helpful, although it can be deduced. On p. 33 the duplication of a 40° isotherm for October might be queried. The final section comprises an extensive set of tables, excellently displayed for statistical or other investigation. The thoughtful reader will admire the devotion of the group of young scientists on whom the observations depend ; for throughout Graham Land and its adjacent islands the sunshine duration is limited and the warmest month can scarcely give a mean above 32°F (0°C) in proximity to so much melting ice, cold sea and persistent low cloud. Yet even at Marguerite Bay where the July mean may lie below - 15°C, rain can occur in midwinter ; and the remarkably low mean pressures found there, still demand elucidation. Observations by earlier parties, notably the British Graham Land Expedition of 1935-37 are briefly discussed, particularly in respect of the astonishingly low mean pressure for March, 1935 which was not accompanied by unusually stormy weather ; as Dr. PEPPER shows, caution must accordingly be exercised for some

time as to what the ultimate "normals" will be. There is a useful bibliography; and it is agreeable to find a brief summary of the earliest meteorological observations known on these bleak islands, kept by a British naval party at Deception Island in 1829.

Appendices on the Antarctic Convergence, and on the pack-ice provide an authoritative summary; and throughout, oceanographers will recognise the value of this work in a region in which the interaction of sea and air is so provocative of enquiry.

The publication is timely; moreover, it is steadily being supplemented by the Annual Meteorological Tables published in a very tidy and praiseworthy form by the Government Printing Office in Stanley. Since January 1st, 1953 a Daily Weather Report, comprising surface observations, synoptic charts, and upper air data from radiosonde ascents has also been issued. These are now regularly maintained at Stanley, and at the Argentine Islands in 65°S. These comprehensive reports, daily and annual, reflect great credit upon Dr. G. A. HOWKINS, the Chief Meteorological Officer, and his small but evidently keen staff. It must have been pleasant for them to observe that in 1953 Stanley's maximum of 77°F. broke a long-standing record. All scientists with interests in this region will look forward to the appearance of the promised five-year summary for 1951-55 which will then form a supplement to Dr. PEPPER'S volume. Of the latter one can already say that it contains perhaps the largest single collection of meteorological data from the Antarctic and sub-Antarctic regions.

GORDON MANLEY

The Electrical Field induced by Ocean Currents and Waves, with Applications to the Method of Towed Electrodes. By M. S. LONGUET-HIGGINS, M. E. STERN and HENRY STOMMEL. Papers in Physical Oceanography and Meteorology, Vol. 13, No. 1, 1954, 37 pp., 29 fig.

Le champ électrique que le champ magnétique terrestre induit dans l'eau en mouvement avait été déjà prévu par FARADAY (1832) et donna lieu à diverses expériences, mais les océanographes se sont surtout intéressés à cette question depuis que von Arx eût montré (1950) que la mesure de la différence de potentiel entre deux électrodes remorquées par un navire fournit, en eau profonde, une évaluation de la vitesse des courants de surface, indépendamment de la vitesse propre du navire. Contrairement à ce qu'on pourrait penser la méthode des électrodes remorquées ne mesure pas la différence de potentiel que produirait dans la mer le champ magnétique terrestre: cette méthode ne fonctionne bien, au contraire, que si la surface de l'eau est équipotentielle, et ce qu'on mesure alors est la force électromotrice induite dans le câble qui va d'une électrode à l'autre, cette force électromotrice étant proportionnelle à la composante de la vitesse du câble normale à celui-ci, donc au courant de surface si la dérive due au vent est négligeable.

La surface de la mer n'est équipotentielle que si la profondeur est suffisante, ou la fond assez conducteur, pour que les forces électromotrices produites dans l'eau par induction du champ magnétique terrestre soient complètement court-circuitées par l'eau immobile sous-jacente, ou le fond. S'il n'en est pas ainsi, l'interprétation des résultats est beaucoup plus difficile, parce que la grandeur mesurée est proportionnelle à la densité du courant électrique à la surface de la mer. LONGUET-HIGGINS, STERN et STOMMEL, qui sont d'excellents théoriciens de cette question, ont calculé ce courant dans un certain nombre de cas schématiques; ils ont considéré aussi l'effet des vagues.

Les conclusions pratiques sont les suivantes: la méthode des électrodes remorquées ne fournit une mesure du courant superficiel que si la profondeur est suffisante pour que la vitesse moyenne sur une verticale, entre le fond et la surface, reste négligeable par rapport à la vitesse en surface, ou bien si le fond est très conducteur; au contraire, un courant de marée qui serait uniforme sur toute la hauteur avec un fond peu conducteur, comme dans la Manche par exemple, conduirait à une différence de potentiel nulle entre les électrodes remorquées. Même dans les cas favorables, les gradients horizontaux de vitesse risquent de donner des effets parasites tandis que les variations de vitesse en fonction du temps n'ont que des effets négligeables. La source d'erreurs la plus importante est probablement liée aux variations du champ magnétique terrestre; par une journée de perturbation magnétique, l'erreur peut atteindre 5 noeuds; cette étude des courants électriques induits dans la mer par les variations du champ terrestre serait à développer.

En résumé, cette étude théorique, rigoureuse et élégante, restera sans doute classique dans l'intéressant problème des champs électriques d'induction dus aux courants marins.

YVES LE GRAND

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Partition of energy between geostrophic and non-geostrophic oceanic motions

G. VERONIS

Abstract—The present investigation re-examines the problem of the response of the ocean to a transient applied wind stress as previously treated by ROSSBY (1938), CAHN (1945) and BOLIN (1953), but with more general conditions on the duration and strength of the applied stress. The chief interest in pursuing this aspect of the problem is to determine in some detail just how much of the energy imparted to the ocean by the wind stress is absorbed by (long) inertio-gravitational motions, and how much goes into quasi-geostrophic current motions.

When momentum is added to the ocean impulsively 74 per cent of the energy goes into inertio-gravitational motions. For an addition of momentum uniformly over a 6 pendulum hour period 51 per cent of the energy is absorbed by the non-geostrophic motions. All but 11 per cent of the energy goes into the geostrophic flow when momentum is added for 12 pendulum hours. The inertio-gravitational motions are almost exclusively confined to the internal mode of behaviour of the stratified ocean. It is shown also that the partition of geostrophic energy between the internal and external modes is dependent on the horizontal scale of the flow, a result which agrees with the corrected result of a previous investigation (VERONIS and STOMMEL, 1955). The process of adjustment of the system is studied quantitatively.

A simpler (asymptotic) solution is derived which is valid for large values of time in a region confined to the vicinity of the main stream. The accuracy of the solution and the domain of its validity are increased with increasing time.

1. INTRODUCTION

WHEN momentum is added to a large region of water in the ocean, the resulting current system adjusts itself toward a state in which the pressure forces are balanced by the Coriolis force which results from the earth's rotation. This geostrophic (or a near geostrophic) balance is, in fact, the principal characteristic of the prevailing large-scale current systems. However, in the build-up of the current systems, non-geostrophic motions may occur if the system does not have time to build up a complete balance between pressure and Coriolis forces. This was suggested by ROSSBY (1938) who noted that in a stratified ocean an initially unbalanced flow will "lose" most of its energy to oscillations which are inertial in character. The non-geostrophic energy of the oscillations is dispersed into the outlying regions until ultimately a geostrophic current (with less energy than the initial kinetic energy of the flow) remains in the source region.

ROSSBY's excellent pioneer work laid the foundation for several further studies. Since he had restricted his investigation to the ultimate behaviour of the flow, the actual process of adjustment was an open question. CAHN (1945) in a quantitative analysis of the model considered by ROSSBY showed that in a homogeneous body of water the energy of the oscillations is radiated away from the initial current system with the speed $c_0 = \sqrt{gD}$, where D is the depth of the ocean and g is the acceleration due to gravity. For an ocean of 4 km depth $c_0 = 200 \text{ m sec}^{-1}$, and it would thus appear that the energy of the oscillations is dispersed so rapidly that the current would be built up within a few hours. BOLIN (1953) undertook the problem of a

stratified ocean with the initially unbalanced current varying continuously in both the vertical and horizontal directions. His results show that the non-geostrophic energy of the internal modes is dispersed with characteristic velocities which are only one or two per cent of those of the homogeneous ocean. In his analysis he found that the stream moves towards an adjustment in which the vertical and horizontal gradients of the current tend to be smoothed.

A recent investigation (VERONIS and STOMMEL, 1955)* on the response of a stratified (two-layer) ocean to variable wind stresses indicates that the time of duration of the wind stress has a considerable effect on the amount of energy absorbed by inertio-gravity oscillations. When momentum is added to the ocean over a period of a half pendulum day or longer, the majority of the energy goes into geostrophic flow. For shorter periods of duration of the wind stress inertio-gravity motions are relatively violent, with most of the non-geostrophic energy flowing into the internal or baroclinic mode. Large-pressure gradients such as those which quickly build up and counteract the growth of inertial oscillations in the barotropic mode are absent in the internal mode. The strongest inertio-gravity motions are internal inertial motions whose magnitudes are controlled by the dynamic stability (the Coriolis force), and which have a period of almost exactly a half pendulum day. Thus the essential characteristics of non-geostrophic motions are very different in the two modes.

It was stated in AVS that the ocean responds barotropically if the time scale of the driving force is less than several months. However, this conclusion was the result of a misinterpretation of the (correct) numerical results.† On closer examination it appears that the geostrophic response of the ocean is very critically dependent on the spatial scale of the flow, and that baroclinic response may be excited for all time scales. Thus the thermocline deviation may be appreciable (of the order of 10 metres) for winds which blow only for a day. The correct interpretation of the results of AVS is that the *maximum* baroclinic effect is not attained except for time scales of the order of several months. This conclusion is due to the effect of β , the variation of the Coriolis parameter with latitude. It does not appear in treatments where the Coriolis parameter is assumed constant.

Mention should be made of the recent study by TEPPER (1955) in which he included the effect of non-linear accelerations in the problem of an impulsive addition of momentum to a stratified fluid. His interesting results indicate the development of a hydraulic jump in the atmosphere just a few hours after the momentum is added to the fluid. However, TEPPER's investigation is subject to some criticism because of his basic assumptions. In the first place, as he has stated, momentum probably is not added impulsively to the ocean or to the atmosphere. Both in AVS and in the present study the finite time of duration of the wind stress is shown to be an important factor in determining the amount of input energy which goes into inertio-gravity motions. Secondly, TEPPER has chosen a very intense unbalanced current – its maximum velocity is approximately 60 metres per second for the atmospheric case which he chose – a factor which would seem to be conducive to strong gravity waves, but which is physically unrealistic. And finally, he considers only the internal mode of behaviour in his treatment. As indicated in AVS, both the barotropic and baro-

* This paper will be referred to as AVS, henceforth.

† The specific passage which is incorrect is in Section 5 of AVS in the discussion of the solution. It states that the net effect of the standing wave and the baroclinic Rossby wave is negligible for several months after the wind begins to blow.

clinic modes are excited by transient additions of momentum. If non-linear effects are included, the two modes interact and the exchange of energy between the two modes would appear to have a profound effect on the nature of the flow.

The present investigation re-examines the questions of the process of adjustment and the partition of energy between geostrophic and non-geostrophic motions in a stratified ocean. A laterally limited distribution of wind stress is prescribed so that a mechanism for the "escape" of non-geostrophic energy is included. The problem is solved for the case in which the wind imparts momentum to the ocean over finite periods of time. The effect of β is neglected here, so that the results are valid only for time periods where such an assumption is plausible. It should be noted, however, that the orientation of the stream has been taken to be east-west in order to minimize the β effect in the vicinity of the stream.

2. STATEMENT OF PROBLEM AND EQUATIONS

Consider a two-layer ocean with each layer homogeneous in density. This structure corresponds roughly to the two masses of water above and below the main thermocline. The ocean is infinite in the horizontal (x, y) plane and is rotating about a vertical axis. It is supposed that the water is initially at rest and that the subsequent motions are small. The wind stress which acts on the surface of the ocean is independent of the x co-ordinate, but is limited in the y direction. Then, under the assumption that the lateral frictional forces are negligible and that there is no frictional transfer of momentum across the interface, the vertically averaged equations describing the flow in the two layers are

$$\frac{\partial u_1}{\partial t} - f v_1 = \frac{\tau}{D_1} \quad (1)$$

$$\frac{\partial v_1}{\partial t} + f u_1 = -g \frac{\partial \eta_1}{\partial y} \quad (2)$$

$$\frac{\partial}{\partial t} (\eta_1 - \eta_2) + D_1 \frac{\partial v_1}{\partial y} = 0 \quad (3)$$

$$\frac{\partial u_2}{\partial t} - f v_2 = 0 \quad (4)$$

$$\frac{\partial v_2}{\partial t} + f u_2 = -g \left[a \frac{\partial \eta_1}{\partial y} + b \frac{\partial \eta_2}{\partial y} \right] \quad (5)$$

$$\frac{\partial \eta_2}{\partial t} + D_2 \frac{\partial v_2}{\partial y} = 0 \quad (6)$$

where u_1, v_1 are the vertically averaged velocities of the upper layer* in the x and y directions respectively; η_1 the deviation of the free surface from its equilibrium position; τ the wind stress component in the x direction; D_1 ($= \text{const.}$) the upper layer equilibrium depth; f the Coriolis parameter (here assumed constant); t the time; g the acceleration due to gravity; and a and b the density ratios $a = \rho_1/\rho_2$,

$$b = \frac{\rho_2 - \rho_1}{\rho_2} = \frac{\Delta \rho}{\rho_2}.$$

* Terms with subscript 2 describe corresponding quantities in the lower layer.

The wind stress is taken as

$$\begin{aligned} \tau &= W = \text{const} & |y| < L \\ &= 0 & |y| > L \end{aligned} \quad \left. \begin{array}{l} \\ \end{array} \right\} 0 < t < t_0 \quad (7)$$

$$= 0 \quad \text{all } y \quad t > t_0.$$

Initial and boundary conditions are :

$$u_1 = v_1 = \eta_1 = u_2 = v_2 = \eta_2 = 0 \quad \left\{ \begin{array}{l} \text{all } y, t = 0 \\ \text{all } t, y = \pm \infty \end{array} \right. \quad (8)$$

The usual methods for solving the problem defined by equations (1) to (8) is to eliminate all the variables except one, and then to solve the resulting differential equation which is of the sixth order in time. A simpler method consists of reducing the equations to normal modes. The problem is then that of finding the solutions to two separate problems, each of which reduces to a differential equation of the third order in time. One of the solutions corresponds to the barotropic or external mode of behaviour of the two-layer ocean. The other corresponds to the baroclinic or internal mode.

Details of the method of normal modes as applied to the two-layer problem are given by GROVES (1954), CHARNEY (1955), and AVS. A résumé of the results will be given here.

The barotropic or external mode is derived by considering the ocean as homogeneous with depth $D = D_1 + D_2$ and density $\rho = \frac{\rho_1 + \rho_2}{2}$. The equations governing the flow are

$$\frac{\partial u^e}{\partial t} - f v^e = \frac{\tau}{D} \quad (9)$$

$$\frac{\partial v^e}{\partial t} + f u^e = -g' \frac{\partial \eta^e}{\partial y} \quad (10)$$

$$\frac{\partial \eta^e}{\partial t} + D \frac{\partial v^e}{\partial y} = 0 \quad (11)$$

where the superscript e is used to denote the external mode.

The equations for the internal or baroclinic mode of behaviour are derived by assuming that the interface responds to disturbances of the free surface in such a manner that there are no pressure gradients in the bottom layer. Then it is seen from equation (5) that

$$\eta_1 = -\frac{(\rho_2 - \rho_1)}{\rho_1} \eta_2. \quad (12)$$

Eliminating η_1 from equations (2) and (3) by means of (12) one finds for the internal mode (denoted by superscript i)

$$\frac{\partial u^i}{\partial t} - f v^i = \frac{\tau}{D_1} \quad (13)$$

$$\frac{\partial v^i}{\partial t} + f u^i = -g' \frac{\partial \eta^i}{\partial y} \quad (14)$$

$$\frac{\partial \eta^I}{\partial t} + D_1 \frac{\partial v^I}{\partial y} = 0 \quad (15)$$

where $g' = \left(\frac{\rho_2 - \rho_1}{\rho_2} \right) g$. Equations (9) to (11) and (13) to (15) are equivalent mathematically. However, in the internal mode gravity is reduced by the factor $\Delta\rho/\rho_2$; consequently, this case will later be referred to as the reduced gravity problem.

The wind stress is again given by (7), and the initial and boundary conditions for the two modes are analogous to those of equations (8).

The solutions to equations (1) to (6) are derived from the solutions to equations (9) to (11) and (13) to (15) by means of the (approximate) relations.*

$$\begin{aligned} \eta_1 &= \eta^e + b \left(\frac{D_2}{D} \right)^2 \eta^I \\ \eta_2 &= \frac{D_2}{D} (\eta^e - \eta^I) \\ v_1 &= v^e + \frac{D_2}{D} v^I \\ v_2 &= v^e - \frac{D_1}{D} v^I \\ u_1 &= u^e + \frac{D_2}{D} u^I \\ u_2 &= u^e - \frac{D_1}{D} u^I. \end{aligned} \quad (16)$$

In the following, actual solutions will be given for a one-layer case only. By interpreting the parameters in the equations approximately, one can derive the solution for the two-layer case with the aid of the relations (16). The equations for the one-layer problem are given by (9), (10), and (11) (without superscripts since the solution corresponds to either mode), the wind stress is given by (7), and boundary conditions are analogous to those described in equation (8).

3. QUASI-GEOSTROPHIC SOLUTION

If the response of the ocean to the wind stress is quasi-geostrophic or quasi-static, the current adjusts itself so that the transverse equation of motion (10) is replaced by

$$fu = -g \frac{\partial \eta}{\partial y}.$$

The solution to the resulting mathematical problem is considerably simpler than the more general one and is†

$$\begin{aligned} \eta &= \frac{W[t]}{2\sqrt{gD}} [e^{x_1} - e^{x_2}]' y < -L \\ &= \frac{W[t]}{2\sqrt{gD}} [e^{-x_1} - e^{x_2}]' - L < y \leq 0 \end{aligned} \quad (17)$$

* These relations are subject to errors of less than one per cent.

† The general problem possesses certain symmetry characteristics. Specifically, the y axis represents a line of symmetry for the velocities and of anti-symmetry for the surface heights. Consequently, all results will be restricted to the right half plane looking downstream, i.e., to the negative y axis.

$$\begin{aligned}
 u &= \frac{W[t]}{2D} [e^{x_2} - e^{x_1}]' y < -L \\
 &= \frac{W[t]}{2D} [e^{-x_1} + e^{x_2}]' - L < y \leq 0
 \end{aligned}
 \tag{18}$$

$$\begin{aligned}
 v &= \frac{W[1]}{2fD} [e^{x_2} - e^{x_1}]' y < -L \\
 &= \frac{W[1]}{2fD} [e^{-x_1} + e^{x_2} - 2]' - L < y \leq 0
 \end{aligned}
 \tag{19}$$

where $[t] = t$ or t_0 and $[1] = 1$ or 0 according as $t < t_0$ or $t > t_0$;

$$z_1 = \frac{f(y+L)}{\sqrt{gD}}, \quad z_2 = \frac{f(y-L)}{\sqrt{gD}}. \tag{20}$$

This solution is the same as the one derived by ROSSBY (1938) if Wt_0/D is interpreted as an initial velocity. For the barotropic ocean the solution represents a strong (practically uniform) downwind current for $|y| < L$, and very weak broad countercurrents on either side. In the reduced-gravity case the current is weak in the centre, rises sharply toward the edges, and is bordered by strong, narrow countercurrents. In both cases the downwind flow is accompanied by a transverse shift of the entire stream to the right so that at every instant the resultant mass distribution is such that geostrophic equilibrium prevails in the transverse direction. Because of the prescribed time dependence of the wind stress the lateral velocity is constant in time during the wind action and vanishes when the wind stops blowing.

The discontinuous nature of the flow at the edges of the stream is a result of the prescribed distribution of the wind stress and the lack of lateral diffusion. If a spatially continuous wind distribution (POISSON, say) were prescribed, the solution would show relatively strong downwind flow in the centre with a continuous change toward the bordering countercurrents on either side. There would be regions of anti-cyclonic and cyclonic shear respectively to the right and left of the centre looking downstream. Such a continuous structure is, however, an unnecessary refinement in the present investigation. The process of adjustment and the energetics of the flow may be studied more easily by the use of the simpler form of the wind stress.

4. GENERAL SOLUTION

The solution to the general one-layer problem (and, consequently, to the two-layer problem if relations (16) are used) is

$$\begin{aligned}
 v &= \frac{Wf}{2D} \int_0^t \int_0^\alpha \{J_0[f\sqrt{\tau^2 - z_2^2}] - J_0[f\sqrt{\tau^2 - z_1^2}]\} J_0[f(\alpha - \tau)] d\tau d\alpha \\
 &\hspace{25em} y < -L \\
 &= \frac{Wf}{2D} \int_0^t \int_0^\alpha \{J_0[f\sqrt{\tau^2 - z_2^2}] + J_0[f\sqrt{\tau^2 - z_1^2}]\} J_0[f(\alpha - \tau)] d\tau d\alpha \\
 &\hspace{15em} - \frac{W}{Df}(1 - \cos ft) \hspace{15em} -L < y \leq 0
 \end{aligned}
 \tag{21}$$

$$\begin{aligned}
 u = & -\frac{Wf}{2D} \int_0^t \int_0^\alpha \frac{z_1}{\sqrt{\tau^2 - z_1^2}} J_1 [f \sqrt{\tau^2 - z_1^2}] d\tau d\alpha - \frac{W}{2D} (t + z_1) H(t + z_1) \\
 & + \frac{Wf}{2D} \int_0^t \int_0^\alpha \frac{z_2}{\sqrt{\tau^2 - z_2^2}} J_1 [f \sqrt{\tau^2 - z_2^2}] d\tau d\alpha + \frac{W}{2D} (t + z_2) H(t + z_2) \\
 & + \frac{W}{2D} \int_0^t \{J_0 [f \sqrt{\tau^2 - z_1^2}] - J_0 [f \sqrt{\tau^2 - z_2^2}]\} J_0 [f(t - \tau)] d\tau \quad (22) \\
 & \qquad \qquad \qquad y < -L \\
 = & \frac{Wf}{2D} \int_0^t \int_0^\alpha \frac{z_1}{\sqrt{\tau^2 - z_1^2}} J_1 [f \sqrt{\tau^2 - z_1^2}] d\tau d\alpha + \frac{W}{2D} (t - z_1) H(t - z_1) \\
 & + \frac{Wf}{2D} \int_0^t \int_0^\alpha \frac{z_2}{\sqrt{\tau^2 - z_2^2}} J_1 [f \sqrt{\tau^2 - z_2^2}] d\tau d\alpha + \frac{W}{2D} (t + z_2) H(t + z_2) \\
 & - \frac{W}{2D} \int_0^t \{J_0 [f \sqrt{\tau^2 - z_1^2}] + J_0 [f \sqrt{\tau^2 - z_2^2}]\} J_0 [f(t - \tau)] d\tau + \frac{W}{fD} \sin ft \\
 & \qquad \qquad \qquad -L < y \leq 0
 \end{aligned}$$

$$\begin{aligned}
 \eta = & \frac{Wf}{2\sqrt{gD}} \int_0^t \int_0^\alpha \{J_0 [f \sqrt{\tau^2 - z_1^2}] - J_0 [f \sqrt{\tau^2 - z_2^2}]\} d\tau d\alpha \quad y < -L \\
 & \qquad \qquad \qquad (23) \\
 = & -\frac{Wf}{2\sqrt{gD}} \int_0^t \int_0^\alpha \{J_0 [f \sqrt{\tau^2 - z_1^2}] - J_0 [f \sqrt{\tau^2 - z_2^2}]\} d\tau d\alpha \quad -L < y \leq 0
 \end{aligned}$$

where z_1 and z_2 are given by equations (20), and

$$\begin{aligned}
 H(t - z) &= 1, \quad t > z \\
 &= 0, \quad t < z.
 \end{aligned}$$

The individual integrals vanish when the argument of the Bessel function becomes imaginary. To include the fact that the wind stops blowing at time t_0 , one must subtract from each of the above expressions a similar expression with t replaced by $t - t_0$.

It is not a simple matter to derive qualitative results from the formal solution. Therefore, numerical results have been computed for three separate cases, corresponding to three values of t_0 , viz., Case I, $t = 0$, Case II, $t_0 = 6$ pendulum hours;* Case III, $t_0 = 12$ pendulum hours. In each case the product Wt_0 is held constant so that equal amounts of momentum are added to the ocean in the three cases. Case I represents an impulsive addition of momentum and is essentially the problem considered by CAHN.

The remaining physical parameters are given the numerical values:

$$\begin{aligned}
 D_1 &= 500 \text{ m} & b &= \frac{\Delta\rho}{\rho_2} = 2 \times 10^{-3} \\
 D_2 &= 3500 \text{ m} & g &= 10 \text{ m sec}^{-2} \\
 D &= D_1 + D_2 = 4000 \text{ m} & L &= 100 \text{ km}
 \end{aligned}$$

The product Wt_0 is taken as $6\pi \times 10^4 \text{ cm}^2 \text{ sec}^{-1}$ corresponding to a wind stress of 3 dynes cm^{-2} acting over a 12 pendulum hour period or of 6 dynes cm^{-2} acting for

* A half-pendulum day (12 pendulum hours) is defined as $2\pi/f$.

6 pendulum hours. For the impulsive case the product $Wt_0 = 6\pi \times 10^4 \text{ cm}^2 \text{ sec}^{-1}$ is equivalent to an initially unbalanced velocity of $1.2\pi \text{ cm sec}^{-1}$ within the limits $|y| < 100 \text{ km}$ in the upper layer.

5. DISCUSSION OF RESULTS

Before presenting the numerical results it would be advisable to recall several facts from previous investigations. Disturbances of the barotropic mode will be propagated to the outlying regions with a speed of $c_0 = \sqrt{gD} = 200 \text{ m sec}^{-1}$, whereas in the internal mode the characteristic velocities are reduced by a factor of 60 (with

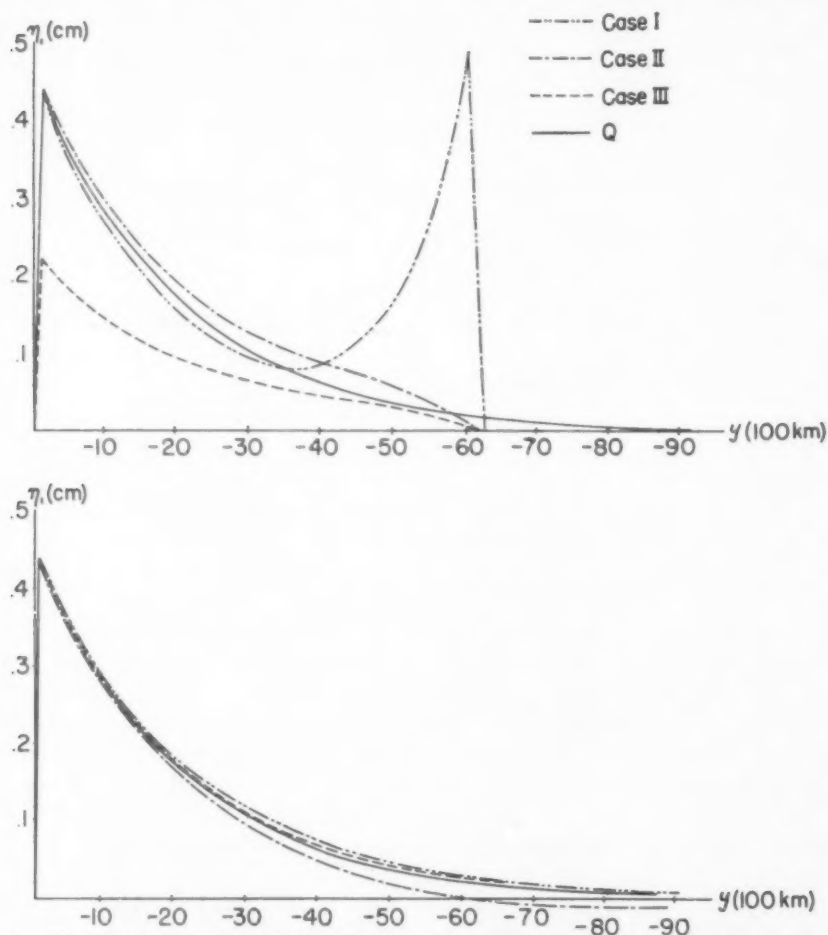


Fig. 1. The spatial distribution ($-9,000 \text{ km} \leq y \leq 0$) of the barotropic free-surface height for the three cases and for the quasi-geostrophic case at $t = 6$ pend. h (upper curve) and at $t = 24$ pend. h (lower curve).

the present choice of parameters). Thus the external disturbances make themselves manifest at distant regions long before those of the internal mode. However, these barotropic inertio-gravitational motions contain very little energy, whereas those of

the baroclinic mode are relatively violent. As a result, it appears appropriate to present the spatial distribution of the variables in two parts. First, the surface heights of the barotropic mode is graphed for a large region ($|y| \leq 10,000$ km) at various times. Secondly, the complete two-layer solution is shown for a region confined to the vicinity of the stream ($|y| \leq 500$ km).

It was noted in Section 3 that the cross-stream velocity for the quasi-geostrophic case vanishes when the wind stops blowing. Hence, any transverse velocities existing after the wind stops blowing are due to non-geostrophic effects. Because the transverse velocity thus yields a good qualitative picture of inertial oscillations, it is considered in some detail.

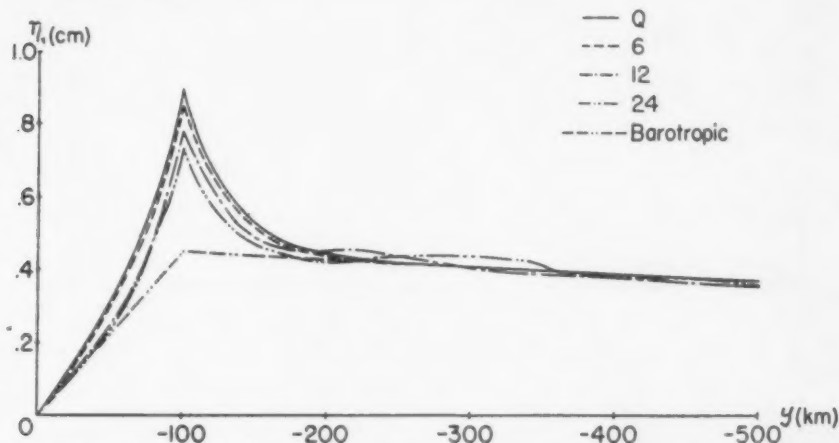


Fig. 2. The spatial distribution of the surface heights η_1 , η_2 and the velocities u_1 , v_1 , u_2 for Case II are shown in the range $500 \text{ km} \leq y \leq 0$. The solution for each variable is given for $t = 6, 12$, and 24 pend. h, and the quasi-geostrophic and barotropic values have been included for η_1 , η_2 and u_1 .

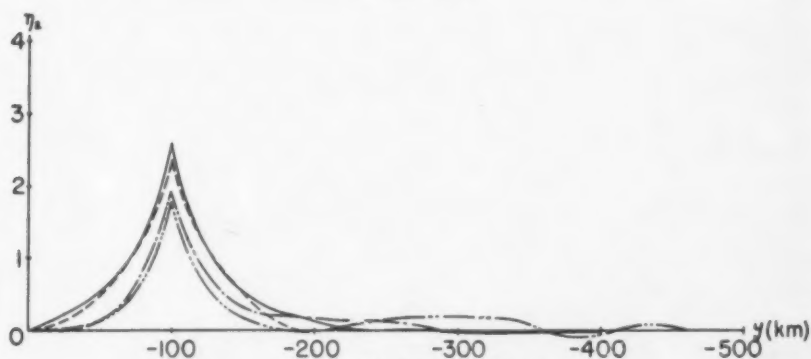


Fig. 3. See legend of Fig. 2.

In order to indicate the distances to which disturbances travel in a short time, a graph of the barotropic surface height vs. distance is shown in Fig. 1 for the three cases and at times $t = 6$ pendulum hours and $t = 24$ pendulum hours after the wind begins to blow. The surface height represents the only (barotropic) variable which may conceivably be measured at large distances from the source region. The

magnitudes of the accompanying velocities are just fractions of 1 mm sec^{-1} , hence the velocities are not shown. The largest surface disturbance is the one resulting from the impulsive addition of momentum. For 6 pendulum hours it has a magnitude of about 0.5 cm at a distance of 6,000 km from the centre of the storm. However, for the two more realistic cases II and III, where momentum is added to the ocean gradually, the surface heights show no such sharp front. After 24 pendulum hours the deviation from the geostrophic value is not appreciable (Fig. 1) and, in fact, with the indicated magnitudes it would be quite unmeasurable.

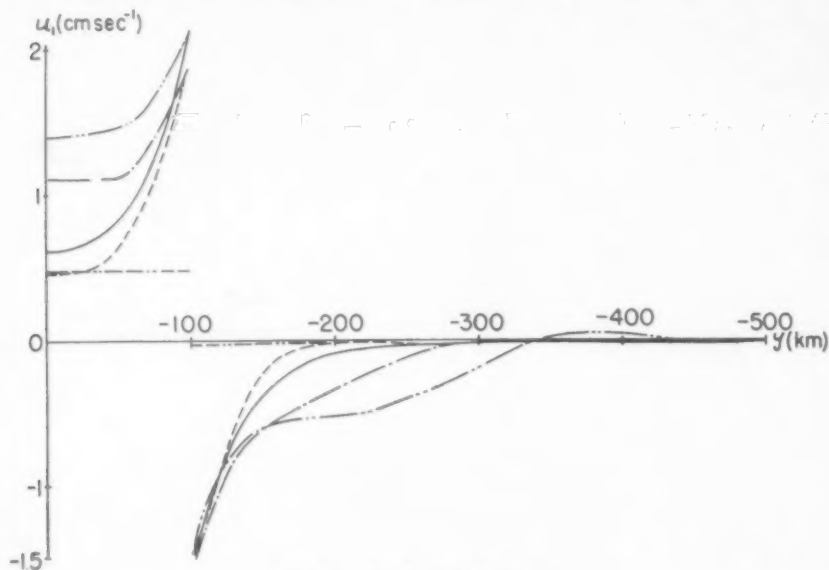


Fig. 4. See legend of Fig. 2.

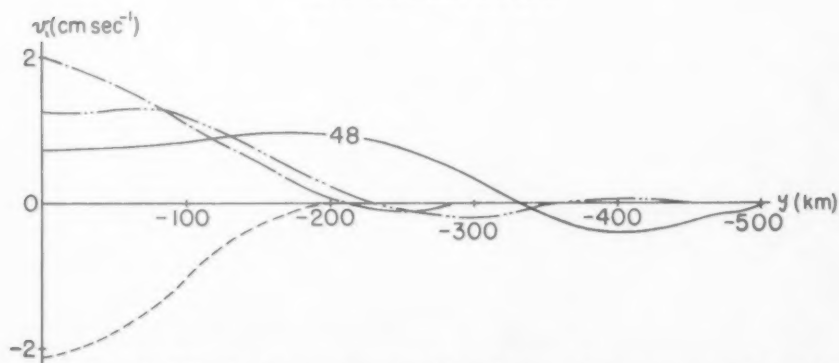


Fig. 5. See legend of Fig. 2. The quasi-geostrophic and barotropic curves are not included here. Because the transverse velocity v_1 illustrates the inertio-gravity motions, the 48 pend. h curve is given.

It should be noted also that within the stream the surface height has no measurable variation from the constant slope. One can infer from AVS that surface disturbances will assume the spatial distribution of the driving force if the scale* of the latter is

* The term "scale" is used here to represent $1/2\pi \times \text{wave length}$.

larger than $\lambda = \frac{\sqrt{gD}}{f}$, the radius of deformation (cf. ROSSBY, 1938). Since $\lambda = 2000$ km, and since the scale here is $2L = 200$ km, no appreciable variation results. It will be seen presently that the internal mode (with $\lambda = 30$ km) shows large variations even within the stream.

A detailed picture of the process of adjustment for case II is shown in Figs. 2 to 6, in which the velocities and surface heights are plotted against y at times $t = 6, 12$ and 24 pendulum hours after the wind starts to blow. The quasi-geostrophic solution and the barotropic quasi-geostrophic solution are also shown for comparison. Case II was chosen because it contains sizeable inertio-gravitational motions (though considerably smaller than those occurring in the less realistic case I).

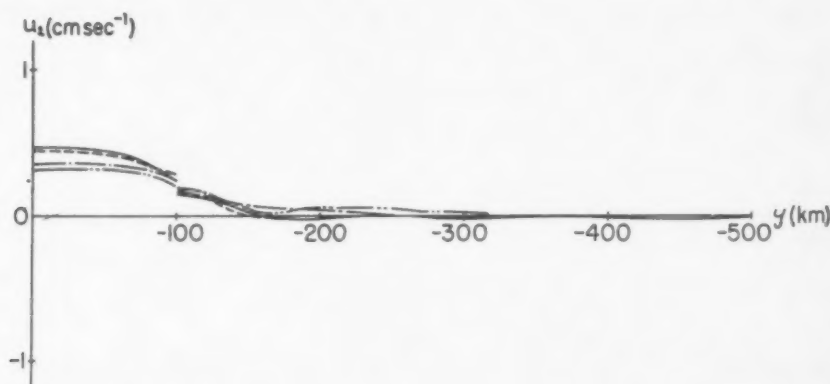


Fig. 6. See legend of Fig. 2. The barotropic component is not shown for u_2 .

The surface of the ocean does not appear to depart very much from the quasi-geostrophic contour. The departure is approximately a millimetre in size at its maximum, a magnitude which would be difficult to detect in the ocean. It is interesting to note that at distances greater than 100 km from the edge of the stream the free surface practically coincides with the barotropic quasi-geostrophic contour. Since the deviation of the thermocline from its equilibrium position is essentially due to the internal mode, the thermocline deviation is simply a magnified reflection of the internal component of the free-surface disturbance.

The principal inertio-gravitational motions are given by the upper-layer velocities. The downstream velocity, u_1 , for example, has a large non-geostrophic component (Fig. 4). Since the quasi-static cross-stream velocity vanishes when the wind stops blowing, the existing transverse velocity depicted in Fig. 5 is purely non-geostrophic.

A characteristic feature of stratified flow which was pointed out in AVS is also indicated by the present results. The rather intense inertio-gravitational velocities are not accompanied by comparable deviations of the free surface and of the interface. The reason is that in the internal mode the non-geostrophic motions are principally inertial in character and do not lead to large mass redistributions. In fact, it is this characteristic of the internal mode which leads to such large inertial

oscillations. In the barotropic case, the transverse shift of the current quickly builds up pressure gradients which act as a damper on the transverse motion and consequently lead to small amplitude oscillations. The period of the oscillation is also affected by the mass distribution in such a way that, except for large-scale currents, the equilibrium state is attained very quickly and high frequency oscillations occur.

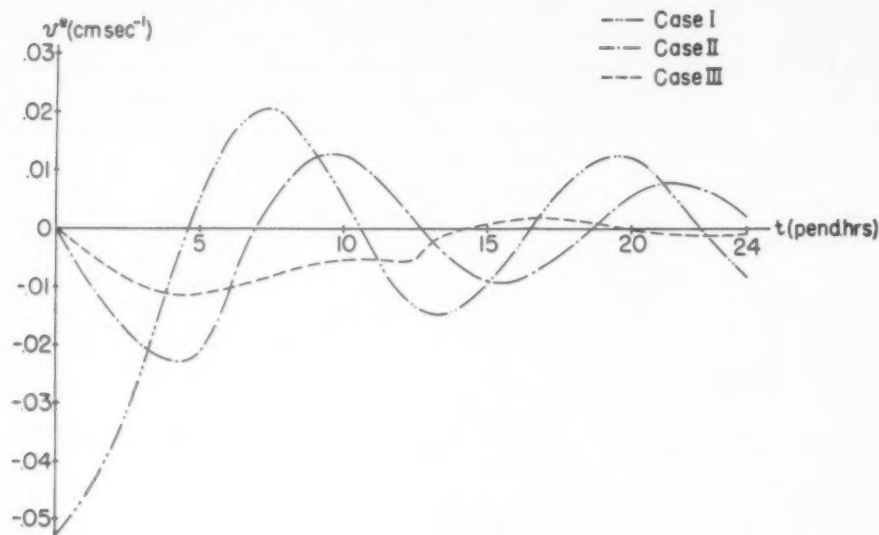


Fig. 7. (a) A comparison of the barotropic components of the cross-stream velocity at the centre of the stream for the three cases and for time $0 \leq t \leq 24$ pend. hr emphasizes the importance of t_0 , the time duration of the wind stress. The curve for case III (where $t_0 = 12$ pend. h) shows very little cross-stream motion after the wind stops, and therefore very small inertio-gravity motions;

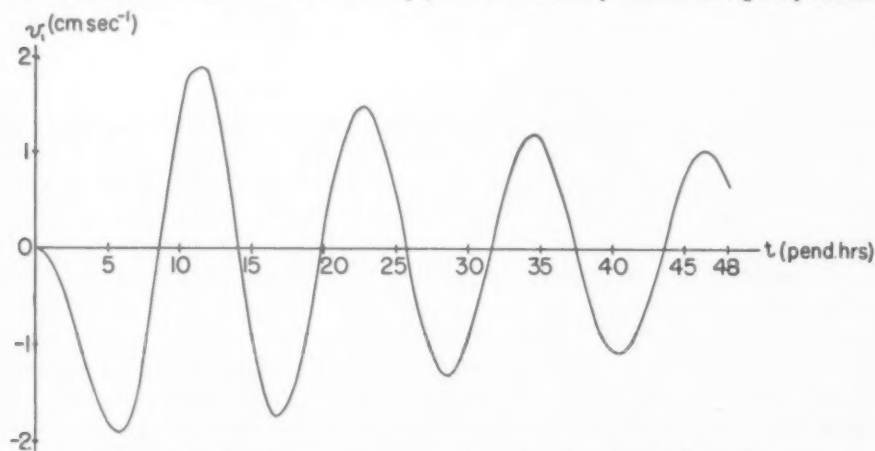


Fig. 7. (b) The transverse velocity at the centre of the stream for case II.

Since in the internal mode gravity is reduced by the factor $b = 2 \times 10^{-3}$, the damping feature of the mass adjustment is also reduced considerably and the oscillations are controlled principally by the dynamic stability factor f . The period of the internal mode oscillations is almost exactly 12 pendulum hours.

The lower layer downstream velocity u_2 is shown in Fig. 6. However, because the contribution of the internal mode is reduced by a factor of $D_1/D_2 = 1/7$, the velocity is close to the geostrophically balanced value.

Further evidence of the dominant role of the internal mode in the non-geostrophic motions is indicated by the distance to which these unbalanced motions have progressed at the various times after the wind has started. After 6 pendulum hours the disturbance is still within 150 km of the edge of the stream. Even after 24 pendulum hours, 500 km marks the greatest distance to which the noticeable inertio-gravitational disturbances have penetrated.

The role of the time of duration of the wind stress in the generation of non-geostrophic motions may be seen quantitatively from a consideration of the transverse velocities. If the transverse velocities are relatively violent, more of the input energy must go into the oscillatory motions. Fig. 7(a) shows, for cases I, II, and III, the barotropic cross-stream velocity component at the middle of the stream plotted as a function of time for a period of 24 hours, after the wind begins to blow. It indicates that inertial oscillations are very strong when momentum is added impulsively, moderate for $t_0 = 6$ h, and very weak when the same amount of momentum is added over a 12 h period. The total cross-stream velocity is considerably larger than the barotropic component, but the conclusion is the same.

The rather violent oscillations which occur in the upper layer are shown in Fig. 7(b) for case II.

6. ENERGY CONSIDERATIONS

From the equations of motion (1) to (6) one may obtain the energy equation of a vertical column of unit cross-section.

$$\begin{aligned} & \frac{D_1 \rho_1}{2} \frac{\partial}{\partial t} (u_1^2 + v_1^2 + \frac{g}{D_1} \eta_1^2) + \frac{D_2 \rho_2}{2} \frac{\partial}{\partial t} (u_2^2 + v_2^2) + \frac{g(\rho_2 - \rho_1)}{2} \frac{\partial \eta_2^2}{\partial t} \\ & = \rho_1 \tau u_1 - \rho_1 g \frac{\partial}{\partial y} (\eta_1 v_1) - \rho_1 g \frac{\partial}{\partial y} (\eta_1 v_2) - g(\rho_2 - \rho_1) \frac{\partial}{\partial y} (\eta_2 v_2) \end{aligned} \quad (24)$$

Integrating equation (24) from $y = -\infty$ to $y = \infty$ and from $t = 0$ to $t = t'$, one finds that the total energy (per thickness unit in the x direction) at time t' is

$$E = \rho_1 \int_{-\infty}^{\infty} \int_0^{t'} \tau u_1 dt dy \quad (25)$$

where the right-hand side represents the input energy. Because the wind stress is given essentially as a body force, the input energy depends upon the upper layer down-wind velocity, u_1 . If strong inertial oscillations exist, the value of u_1 is affected and consequently the input energy may differ markedly from the quasi-geostrophic input energy.

Energy computations for the three cases were made, and it was found that the portion of the input energy which remains in the geostrophic flow is 25 per cent for case I, 49 per cent for case II, and 89 per cent for case III. Thus the majority of the energy which is added impulsively goes into inertial oscillations, whereas if the energy is added over a 12 pendulum hour period all but 11 per cent of the energy goes into the geostrophically balanced flow. These results agree qualitatively with those given in AVS. The present values for the non-geostrophic energy are smaller than

those given for the stratified ocean by ROSSBY, who considered only the internal mode for the two-layer ocean. Table 1 shows the percentage of energy absorbed by the geostrophic flow computed for the barotropic and the reduced gravity oceans individually, and for the complete two-layer case.

Table 1. Percentage of input energy retained in geostrophic flow.

	Case I	Case II	Case III
Duration of wind (pend. h.)	0	6	12
Barotropic model	95%	99%	99.9%
Reduced gravity model	16%	33%	83%
Two-layer model	26%	49%	89%

Because of the simplicity of the quasi-geostrophic solution and because of the linearity of the problem, the calculation for the partition of energy into the internal and external modes of the balanced motion can be derived with ease. Equation (25) can be written

$$E = \rho_1 \int_{-\infty}^{\infty} \int_0^t \tau u_1 dt dy = \rho_1 \int_{-\infty}^{\infty} \int_0^t \tau u^e dt dy + \rho_1 \frac{D_2}{D} \int_{-\infty}^{\infty} \int_0^t \tau u^i dt dy. \quad (25a)$$

The two integrals on the right represent respectively the barotropic and the baroclinic input energies. Since the problem is linear and the two modes are normal, there is no transfer of energy from one mode to the other, and the initial distribution of energy represents the subsequent distribution. If the integral expressions on the right in (25a) are written as E^e and E^i respectively, the ratio of the baroclinic to the barotropic absorption of the energy is

$$\frac{E^i}{E^e} = D_2 \sqrt{\frac{b}{D_1 D}} \left[\frac{1 - e^{-2fL/\sqrt{bgD_1}}}{1 - e^{-2fL/\sqrt{gD}}} \right]. \quad (26)$$

It will be noted that, when the scale of the motion is much larger than either radius of deformation*, i.e., $L > \frac{\sqrt{gD}}{f}$, and $L > \frac{\sqrt{bgD_1}}{f}$, then

$$\frac{E^i}{E^e} = D_2 \sqrt{\frac{b}{D_1 D}} = 0.117. \quad (27)$$

For smaller-scale motions the ratio of baroclinic to barotropic energy is dependent on the scale of the flow. E.g., when the scale is smaller than the barotropic radius of deformation more energy goes into the baroclinic mode. In Fig. 8 the distribution of E^e/E^i is illustrated for various values of L . For very-small-scale motions the majority of the energy goes into the baroclinic mode.

It is interesting to note that the functional dependence of the wind stress on time does not enter into the present result. This fact becomes more significant if one considers, say, a moving wind system of the form

* Equation (26) appears to be unrealistic for the case where $L \rightarrow \infty$. Actually the boundary conditions as well as the basic assumptions are invalid for this special case.

$$\tau = g(t) h(y - ct)$$

By a change of variables

$$t = T, \quad y - ct = \xi$$

the wind stress takes the form

$$\tau = g(T) h(\xi)$$

and the transformed equations governing the balance flow depend on T only in parametric form. Thus the energy distribution of the balance flow is independent of the time in the latter case also.

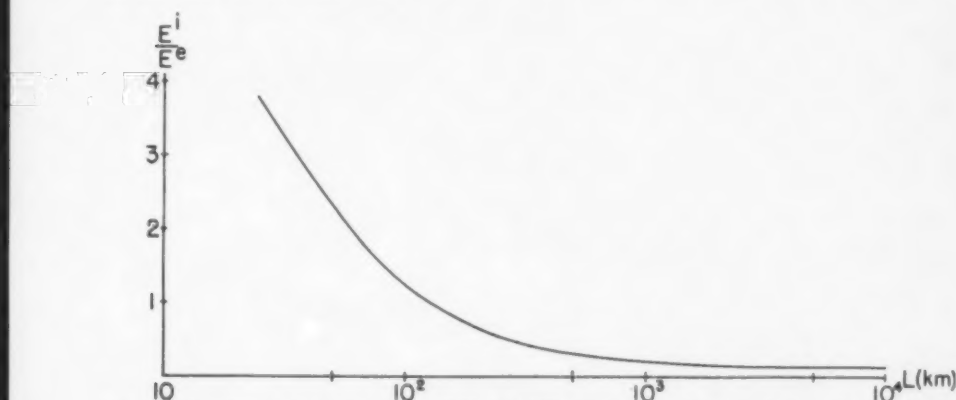


Fig. 8. The figure shows the ratio E^i/E^e for different values of the scale L . E^i and E^e are the geostrophic energies of the internal and external modes respectively.

One should keep in mind the fact that the β effect has been neglected in the present investigation, and the treatment is correct only where this assumption is valid. The above result, for example, is not true for time scales of more than a few days, since the β effect makes itself manifest by keeping the motion finite in the form of westward moving waves. For sufficiently small time scales, however, the waves may be linearized and the β effect is not important (see AVS).

7. ASYMPTOTIC SOLUTION

The general solution given in Section 4 is complicated and, in its present form, poses serious computational problems if one wants to study the behaviour of the ocean long after the wind has stopped blowing. Therefore, it is desirable that a simpler, approximate solution which is valid for large values of t be available. One can derive such an asymptotic solution in the present case by means of a special technique derived by VAN DER WAERDEN (1951). Because of the lengthy manipulations involved, the derivation has been relegated to the appendix and the results only are presented here. It is necessary only to note that the largest terms neglected are of the order $\frac{y^2}{gDr^2}$ as compared to unity, so that if one is interested in large values of y , correspondingly larger values of t are necessary before the solution becomes admissible. Note that in the baroclinic mode gravity is reduced by the factor 2×10^{-3}

and the depth by the factor $1/7$ so that the restrictive conditions are considerably more severe than they are for the barotropic case.

The asymptotic solution is

$$v = \frac{WL}{D\sqrt{gD}} \sqrt{\frac{2}{\pi}} \left[\frac{1}{\sqrt{f(t-t_0)}} \cos [f(t-t_0) + \pi/4] - \frac{1}{\sqrt{ft}} \cos (ft + \pi/4) \right]' \text{ all } y \quad (28)$$

$$\begin{aligned} u &= \frac{Wt_0}{2D} [e^{z_2} - e^{z_1}] + \frac{WL}{D\sqrt{gD}} \sqrt{\frac{2}{\pi}} \left[\frac{1}{\sqrt{f(t-t_0)}} \sin [f(t-t_0) + \pi/4] \right. \\ &\quad \left. - \frac{1}{\sqrt{ft}} \sin (ft + \pi/4) \right]' y < -L \\ &= \frac{Wt_0}{2D} [e^{z_2} - e^{z_1}] + \frac{WL}{D\sqrt{gD}} \sqrt{\frac{2}{\pi}} \left[\frac{1}{\sqrt{f(t-t_0)}} \sin [f(t-t_0) + \pi/4] \right. \\ &\quad \left. - \frac{1}{\sqrt{ft}} \sin (ft + \pi/4) \right]' -L < y \leq 0 \end{aligned} \quad (29)$$

$$\begin{aligned} \eta &= \frac{Wt_0}{\sqrt{gD}} \left(e^{z_1} - e^{z_2} + \frac{1}{ft_0} \sqrt{\frac{2}{\pi ft}} \left[\left(1 - \left(\frac{z_2}{ft} \right)^2 \right)^{3/4} \sin (\sqrt{f^2 t^2 - z_2^2} + \pi/4) \right. \right. \\ &\quad \left. \left. - \left(1 - \left(\frac{z_1}{ft} \right)^2 \right)^{3/4} \sin (\sqrt{f^2 t^2 - z_1^2} + \pi/4) \right] \right. \\ &\quad \left. - \frac{1}{ft_0} \sqrt{\frac{2}{\pi f(t-t_0)}} \left[\left(1 - \frac{z_2^2}{f^2(t-t_0)^2} \right)^{3/4} \sin (\sqrt{f^2(t-t_0)^2 - z_2^2} + \pi/4) \right. \right. \\ &\quad \left. \left. - \left(1 - \frac{z_1^2}{f^2(t-t_0)^2} \right)^{3/4} \sin (\sqrt{f^2(t-t_0)^2 - z_1^2} + \pi/4) \right] \right]' y < -L \end{aligned} \quad (30)$$

where z_1 and z_2 are given by eq. (20). For $-L < y \leq 0$ the expression for η is the same as (30), with z_1 replaced by $-z_1$.

Numerical results will not be given for the asymptotic solution since it is possible to discuss the general features of the flow from the formal expressions.

Two important results are obtained immediately from an inspection of eqs. (28) to (30). As $t \rightarrow \infty$ the flow in the vicinity of the stream approaches the quasi-geostrophic flow derived earlier. ROSSBY indicated this fact in his original investigation, and the result has been employed by later writers on the subject. CAHN also derived the expression (28) for case I.*

It appears that an inconsistency exists in the non-geostrophic parts of the approximate solution because η is dependent on the y co-ordinate (through z), whereas u and v appear to be independent of y . Actually however, the above expressions represent the principal contributions for large values of the time and the terms containing y in the expression for u and v are of second order. The physical reason for this seemingly anomalous behaviour is that the non-geostrophic motions represent a "balance" between the accelerative forces $\left(\frac{\partial}{\partial t} \text{ terms} \right)$ and the Coriolis forces. The

* The expressions (28) to (30) are indeterminate for the impulsive case. However, one can derive similar expressions for Case I by the use of l'Hospital's rule or by a separate treatment for this special case.

surface disturbances are principally due to the geostrophically balanced flow, and consequently have smaller non-geostrophic contributions. A quantitative confirmation of this result is indicated in Figs. 2 to 6 where the velocities deviate from the quasi-geostrophic values by a considerable amount; the surface heights show considerably smaller deviations from the balanced values. The same conclusion was drawn in AVS from the complete solution to the simpler (spatially periodic) system which was investigated.

Thus, within a limited region (the size of which increases with time) centred about $y = 0$, the transverse velocity is uniform. The maximum amplitude of the velocity decreases as $\frac{1}{\sqrt{ft}} \sqrt{\frac{2t-t_0}{t-t_0}}$ with increasing time and the period of the oscillations is 12 pendulum hours. Each of these results are verified by the graphs representing the later stages of the flow (Figs. 7 (a) and 7 (b), and the 48 pendulum hour curve of v in Fig. 4).

Many other interesting aspects of the flow may be seen qualitatively from the asymptotic solution. E.g. if one confines his attention to the region lying within 5,000 km of the strip, then a maximum error of 17 per cent is involved when one replaces the general barotropic solution by the approximate solution for $t = 1$ pendulum day. For a maximum error of 17 per cent, the asymptotic solution for the baroclinic mode must be restricted to the region lying within 200 km of the strip and to $t \geq 2.5$ pendulum days. Hence, it is evident that the baroclinic non-geostrophic motions are considerably more violent than the corresponding barotropic motions, and they remain in the vicinity of the source region for a much longer period of time.

8. SUMMARY AND CONCLUSIONS

The response of a two-layer ocean subjected to wind stresses which vary in time has been investigated in some detail. Attention has been confined to cases where the wind blows over the ocean for periods not exceeding a half pendulum day so that strong non-geostrophic motions occur. A study of the partition of energy indicates that the percentages of input energy absorbed by inertial oscillations are 74 per cent, 51 per cent and 11 per cent when the momentum is added impulsively, over a 6 pendulum hour period, and over a 12 pendulum hour period respectively. For longer periods of duration of the wind stress a previous investigation (AVS) has shown that the major portion of the energy flows into the geostrophically balanced flow.

The principal non-geostrophic motions which take place are the result of the density stratification of the ocean. For the barotropic mode of behaviour the resulting inertial oscillations are negligible, absorbing a maximum of 5 per cent of the input energy in the most extreme case. The energy of internal non-geostrophic motions is radiated away with low characteristic velocities (3 m sec^{-1}) so that these motions remain near the source region for a relatively long time.

The actual magnitudes of the non-geostrophic velocities given in this investigation are smaller than those which can ordinarily be measured in the ocean. It would appear therefore that they would not be easily detected in nature, especially as the irregular action of the winds would tend to obscure the motions. However, there are several features of these wind-driven motions which have not been included in

the present analysis, and which may lead to more observable motions. Specifically, the vertical variation (due to vertical shearing stresses) of inertial motions is such that the strongest velocities are confined to the surface layers and the magnitude quickly decreases with depth. The magnitudes given here are for the vertically averaged velocities and are considerably smaller than the (usually observed) surface velocities. It is evident also that the depth of the ocean has a strong influence on the amplitudes of the inertial motions. This is most apparent in the asymptotic solution. For shallower basins the wind stress imparts momentum to smaller columns of water and the resulting motions are correspondingly stronger.

The inertio-gravitational motions which arise are principally the result of the interaction between accelerative forces and Coriolis forces. The corresponding pressure gradients (deviations of the surface heights) are about an order of magnitude smaller, which indicates that inertial oscillations do not give rise to correspondingly large mass redistributions but instead are principally horizontal motions whose magnitude and period are determined by the Coriolis term.

The geostrophic response of the ocean is dependent on both the time and space scales of the flow. If the time scale is less than the quarter period of the barotropic ROSSBY wave, the β effect is not important and the results of the present investigation are applicable. Specifically, for short periods, the geostrophic response of the ocean is primarily baroclinic for space scales much smaller than the barotropic radius of deformation. For large-scale flow (whose scale is larger than the barotropic radius of deformation) most of the geostrophic energy is contained in the barotropic mode. In the intermediate range the absorption of geostrophic energy lies between the two extremes and its actual partition is determined by quantitative considerations.

For time scales comparable to or larger than the period of the barotropic ROSSBY wave the effect of β becomes important. The barotropic ROSSBY wave reaches its maximum amplitude and begins to decrease, whereas the baroclinic ROSSBY wave continues to increase for a longer period of time. It is evident therefore that the response of the ocean becomes more baroclinic the longer the time scale.

The deviation of the thermocline from its equilibrium position is approximately 3 metres at its maximum for a wind stress of 3 dynes cm^{-2} acting for 12 pendulum hours. Wind systems which last a few days therefore should give rise to measurable disturbances in the position of the thermocline (of the order of 10 to 20 metres).

The deep-water velocities are small. Within the framework of the present model nothing short of unreasonably high winds acting for periods of weeks could give rise to detectable deep-water motions.

An asymptotic solution was derived which is valid in the neighbourhood of the stream for large values of time. This approximate solution indicates that broad regions of water near the source region move transverse to the stream with the same velocity. The transverse velocity is inertio-gravitational and has a period of a half pendulum day. The magnitude of the velocity decreases with time as $\frac{1}{\sqrt{ft}} \sqrt{\frac{2t-t_0}{t-t_0}}$.

Acknowledgement—The author wishes to express his appreciation to H. STOMMEL, J. G. CHARNEY, and N. A. PHILLIPS for a number of stimulating discussions on this topic.

APPENDIX

IN ORDER to investigate the asymptotic behaviour of the solution it is preferable to work with dimensionless variables. Therefore the following substitutions will be made

$$V = \frac{vD}{Wt_0}, \quad t' = tf \quad (\text{A.1})$$

Take the Laplace transform of V with respect to t' , i.e.,

$$\bar{V} = \int_0^\infty V e^{-pt'} dt'$$

Then one has expressions of the type

$$\bar{I} = \frac{1}{p(p^2 + 1)} e^{-z\sqrt{p^2 + 1}} \quad (\text{A.2})$$

The inversion integral for the above expression is

$$I = \frac{1}{2\pi i} \int_{\Gamma'} \frac{e^{-t'[-p + \beta\sqrt{p^2 + 1}]} dp}{p(p^2 + 1)} \quad (\text{A.3})$$

where $\beta = z/t$ and Γ' is the path in the p plane shown in Fig. 9 (a).

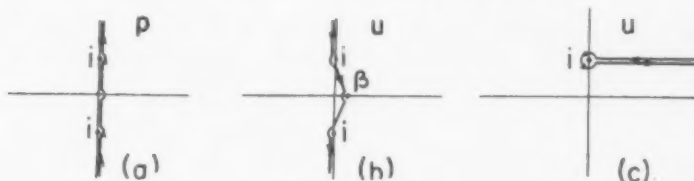


Fig. 9. See text.

VAN DER WAERDEN's method for asymptotically evaluating integrals of the type

$$I = \int_{\Gamma'} w e^{-tu} dv \quad \text{for large } t \quad (\text{A.4})$$

(where $w = w(v)$, $u = u(v)$, and Γ' is a path in the v plane) consists of (1) writing w and v as functions of u ; (2) transforming the path of integration to the u plane; (3) deforming the path Γ' so that integrations need be taken only along lines parallel to the real axis in the u plane and around poles and branch points; (4) expanding the resultant expressions into power series about each singularity; and (5) evaluating the resulting simple integrals. In the event of near-coincidence of a pole and a branch point, the effect of the pole is subtracted out of the expansion about a branch point.

In (A.3) the contribution from the pole at the origin does not require any special techniques and can be evaluated simply,

$$\left. \frac{e^{-t'[-p + \beta\sqrt{p^2 + 1}]} }{p^2 + 1} \right|_{p=0} = e^{-z}. \quad (\text{A.5})$$

Let $u = -p + \beta\sqrt{p^2 + 1}$, and let the inverse transformation be $p = \frac{-u + \beta\sqrt{u^2 + \alpha^2}}{\alpha^2}$ where $\alpha^2 = 1 - \beta^2$. Then the integral assumes the form

$$I = \frac{\alpha^4}{2\pi i} \int_{\Gamma} \frac{e^{-u t'} du}{[-u + \beta\sqrt{u^2 + \alpha^2}][u\beta - \sqrt{u^2 + \alpha^2}]\sqrt{u^2 + \alpha^2}} \quad (\text{A.6})$$

where Γ is the path in the $u = u_1 + iu_2$ plane shown in Fig. 9 (b). There are branch points at $u = \pm i\alpha$ and poles at $u = \pm i, 0$.

Consider the branch point at $u = i\alpha$. Let $m = \sqrt{u - i\alpha}$ be positive above the line $u_2 = \alpha$ and negative below. There is a pole at $u = i$ near $u = i\alpha$. Hence, choose $l = m - \sqrt{i - i\alpha}$. Then if the integrand be expanded into powers of l , the expansion is

$$-\frac{1}{2\alpha^4 ml} \left\{ 1 - \frac{l}{2\alpha^4} \left[i\beta\alpha^2 \sqrt{i + i\alpha} + \frac{(i + 2\alpha + 2\alpha^2)\alpha^2}{\sqrt{i + i\alpha}} \sqrt{\frac{i - \alpha}{i + \alpha}} + O(l^2) \right] \right\}. \quad (\text{A.7})$$

Neglecting all but the first term in the expansion amounts to neglecting terms of order $1/l'$ (all comparisons are made with respect to terms of order 1). Then

$$I_1 = -\frac{1}{4\pi i} \int \frac{e^{-ul'} du}{ml}. \quad (\text{A.8})$$

Now

$$\frac{1}{ml} = \frac{1}{m[m - \sqrt{i - i\alpha}]} = \frac{1}{\sqrt{i - i\alpha}} \left[\frac{1}{m - \sqrt{i - i\alpha}} - \frac{1}{m} \right]. \quad (\text{A.9})$$

The term $\frac{1}{m - \sqrt{i - i\alpha}}$ represents the contribution of the pole at $u = i$. Using the relationship $u = m^2 + i\alpha$ reduces (A.8) to the form

$$I_1 = \frac{e^{-iat'}}{2\pi i} \int_{-\infty}^{\infty} \frac{1}{\sqrt{i - i\alpha}} \left[\frac{1}{m - \sqrt{i - i\alpha}} - \frac{1}{m} \right] e^{-m^2 t'} m dm \quad (\text{A.10})$$

where the limits arise from the fact that the path of integration is reduced to integrating along the upper part of $u_2 = \alpha$ from ∞ to the branch point and then back along the lower part of $u_2 = \alpha$ from the branch point to ∞ , Fig. 9 (c).

The contribution of the second term in the integrand, viz., $1/m$, yields

$$-\frac{e^{-iat'}}{2\pi i \sqrt{i - i\alpha}} \int_{-\infty}^{\infty} e^{-m^2 t'} dm = \frac{e^{-iat'}}{2i \sqrt{\pi t'} \sqrt{i - i\alpha}}. \quad (\text{A.11})$$

The evaluation of the remaining term

$$\frac{e^{-iat'}}{2\pi i \sqrt{i - i\alpha}} \int_{-\infty}^{\infty} \frac{e^{-m^2 t'} dm}{m - \sqrt{i - i\alpha}} \quad (\text{A.12})$$

is somewhat more complicated and requires the use of the gamma functions and their integrals. The resultant contribution is

$$\frac{e^{-iat'}}{2\pi i \sqrt{i - i\alpha}} \sqrt{\frac{\pi}{t'}} - \frac{e^{-lt'}}{2} - \frac{z}{\sqrt{2\pi t'}} e^{-l(t' + \pi/4)} \quad (\text{A.13})$$

where terms of order $z^2/6t'$ are neglected.

Thus the total value of I_1 results from addition of (A.11) and (A.13) and is

$$I_1 = -\frac{e^{-lt'}}{2} - \frac{z}{\sqrt{2\pi t'}} e^{-l(t' + \pi/4)}. \quad (\text{A.14})$$

If the above computations are carried through for the branch point at $u = -i\alpha$, the contribution is found to be

$$I_2 = -\frac{e^{lt'}}{2} - \frac{z}{\sqrt{2\pi t'}} e^{l(t' + \pi/4)}. \quad (\text{A.15})$$

Thus,

$$I = e^{-z} - \cos t' - z \sqrt{\frac{2}{\pi t'}} \cos(t' + \pi/4) \quad (\text{A.16})$$

where the first term in (A.16) is due to the contribution at the origin.

A similar expression with $t' - t_0'$ replacing t' is provided by adding the effect of t_0 . Thus the first term cancels (being independent of t') and the complete value of v , subject to the approximations made, is given by equation (28) in Section 7.

Treatment of the expressions for u and η are similar though the denominators vary. In η there are no poles at $u = \pm i\alpha$ and, consequently, the solution is more easily obtained.

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REFERENCES

- BOLIN, B. (1953), The adjustment of a non-balanced velocity field towards geostrophic equilibrium in a stratified fluid. *Tellus*, **5**, No. 3, 273-285.
- CAHN, A. (1945), An investigation of the free oscillations in a simple current system. *J. Meteorol.*, **2**, No. 2, 113-119.
- CHARNEY, J. G. (1955), Generation of ocean currents by wind. *J. Mar. Res.*, **14**, No. 3.
- GROVES, G. W. (1954), Dynamic model of a two-layer ocean under influence of atmospheric and coastal boundary, Tech. Rept. No. 54-22 Scripps Institution of Oceanography, 27 pp. (unpublished).
- ROSSBY, C. G. (1938), On the mutual adjustment of pressure and velocity distribution in certain simple current systems. *J. Mar. Res.*, **1**, 239-263.
- TEPPER, M. (1955), On the generation of pressure jump lines by the impulsive addition of momentum to simple current systems. *J. Meteorol.*, **12**, No. 4, 287-297.
- VAN DER WAERDEN (1951), On the method of saddle points. *Appl. Sci. Res. B* **2**, 33-45.
- VERONIS, G. and STOMMEL, H. (1955), The action of variable wind-stresses on a stratified ocean. *J. Mar. Res.*, **14**, No. 3.

A contribution to the natural history of the white-tip shark, *Pterolamiops longimanus* (Poey)

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Abstract—Until recently little has been known about the common, pelagic shark, *Pterolamiops longimanus*. Data gathered during recent offshore cruises show it to be abundant and widely distributed in the warm waters of the western North Atlantic. It occurs at a wide range of salinities but withdraws from some waters when the temperature gets as low as about 21°C. It is rarely present in water shallower than about 100 fathoms. In a sample of 110 sharks few were over 250 cm in total length, although the maximum size reported in the literature is much longer. Fish and cephalopods are the most frequent food items in white-tip stomachs. White-tips are cautious, persistent, and sluggish in their behaviour. They are responsible for considerable damage to long line caught tuna in the Gulf of Mexico. Geographical sexual segregation is a feature of white-tip life history. Fragmentary data indicate that the mating and pupping season is in the late spring or early summer and that the gestation period is about one year. Females probably first mate at a length of about 200 cm, and probably bear young in alternate years thereafter. The number of pups per litter varies from 2 to 9 with a mean of about 6. Shark suckers (*Remora remora*), pilotfish (*Naucrastes ductor*), dolphin (*Coryphaena hippurus*) and a copepod parasite or parasites are common associates of the white-tip.

INTRODUCTION

RECENTLY, BIGELOW and SCHROEDER (1948), in their monograph "Sharks," wrote of the white-tip, "Astonishingly little is known of the habits of *longimanus*, considering that it is one of the members of its genus that has been recognized the longest."

That this is true is probably explained by the animal's rather strict oceanic habit which makes it largely unavailable to seaside naturalists. However, with an increasing number of offshore surveys it is becoming better known. MATHER and DAY (1954) found it to be widespread, abundant, and the commonest pelagic shark in the warm parts of the North Atlantic. BULLIS (1955) regards this shark as responsible for most of the damage to long line-caught tuna in the Gulf of Mexico, although it was quite unknown from that area prior to an investigation of offshore waters begun in 1950 by the U.S. Fish and Wildlife Service.

Although BIGELOW and SCHROEDER (1948) also assume the white-tip to be common in the Mediterranean on the basis of statements by MÜLLER and HENLE (1841), GÜNTHER (1870), DODERLEIN (1881), and others, TORTONESE (1951) states that its presence there is not now demonstrable by museum specimens or other verifiable records. MAUL (1955) records the species from Madeira.

The authors have been gathering data on the Atlantic white-tip shark independently during the course of other work for the past few years. BACKUS has made observations from the Research Vessels *Atlantis* and *Bear* of the Woods Hole Oceanographic

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Fig. 1. White-tip shark (*Pterolamiops longimanus*) with two pilotfish, photographed at sea by JAN HAHN, Woods Hole Oceanographic Institution.

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Institution, and SPRINGER has made observations from the Exploratory Fishing Vessel *Oregon* of the U.S. Fish and Wildlife Service. ARNOLD has furnished records of captures made from the U.S.F.W.S. Vessel *Alaska* and from recent cruises of the *Oregon*. In many cases, in the absence of the authors, fishing was done and records kept by co-workers or crew members of the above vessels. Furthermore, we have

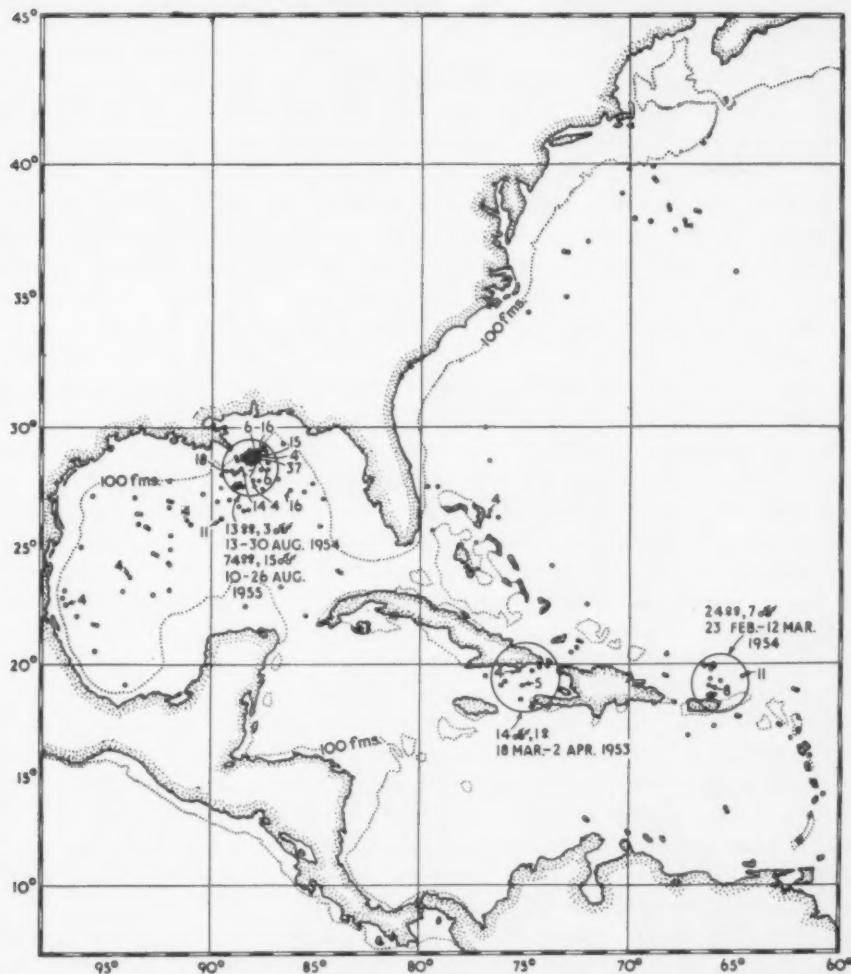


Fig. 2. Distribution of white-tip shark captures. The scanty literature records are omitted. Three areas in which sexual segregation has been noted are encircled. All captures save one are outside the 100-fathom curve.

used records furnished by W. W. ANDERSON of captures made from the U.S.F.W.S. Research Vessel *Theodore N. Gill*, and Mr. WILLIAM C. SCHROEDER of the Woods Hole Oceanographic Institution has given us records of captures from *Caryn* and *Cap'n Bill II*. Because of this diversity of sources, our data vary in their completeness and do not show the geographic distribution of the fishing effort which produced them.

Our records (Fig. 2) are mostly from hand line and long line captures near the surface, but some sight records are included. Statements concerning the absence of white-tips from inshore waters and from parts of the Straits of Florida are largely made on the basis of SPRINGER's observations during commercial shark fishing operations on the continental shelf off Florida, in the Gulf of Mexico, off the Caribbean coasts near Nicaragua and Trinidad, and off the coasts of the Guianas between 1930 and 1949.

NOMENCLATURE

The species included in *Carcharhinus* as previously understood (see BIGELOW and SCHROEDER, 1948) were divided into three genera in a recent revision of western-Atlantic Carcharhinidae (SPRINGER, 1950a ; 1951). A primary division of these sharks was based on the presence or absence of a median, longitudinal ridge in the skin between the first and second dorsal fins. *Carcharhinus* was retained for the smooth-backed members of the older genus. The ridge-backed members were divided between *Eulamia* (with acuminate first dorsal and pectorals) and *Pterolamiops* (with broadly rounded first dorsal and pectorals). The white-tip belongs to the latter genus in this classification.

In general, though observations have not covered all species, the large ridge-back, carcharhinid sharks in the western North Atlantic are oceanic, although they may at times range into coastal waters. Conversely, western North Atlantic observations from off the shelf are lacking for any smooth-backed carcharhinids excepting two doubtful observations of *Negaprion brevirostris* (Poey). The smooth-backed species of the genus *Carcharhinus* (as restricted by SPRINGER) are shallow water species particularly abundant near mouths of large rivers. *Eulamia* contains sharks of the reefs, the outer parts of the continental shelf, and, to some extent, the high seas. *Pterolamiops* is strictly pelagic.

Field identification of the white-tip shark is easily made because it is the only large carcharhinid having a high first dorsal that is broadly and evenly rounded at its apex. The very large pectorals with broadly rounded tips are also distinctive. The middorsal ridge is readily observed in freshly caught late embryos, young, and adults, but its existence in preserved ones cannot always be demonstrated. Usually the pectorals and the first dorsal are tipped with white, but the amount of white showing is variable and its complete absence is fairly common. Black tips on the pelvics, second dorsal, anal, and lower caudal characterized a young example collected off Tampico, Mexico. This distribution of black spots is shown in MAUL's figure (1955, Fig. 9). The black spots, if regularly present in young white-tips, tend to disappear in preserved specimens, and become obscure in living white-tips as they approach maturity. The pectorals and first dorsal fin of the Tampico specimen were not white-tipped, although the first dorsal was somewhat lighter near the tip.

DISTRIBUTION

BIGELOW and SCHROEDER (1948) suggested that the physical factor which primarily determines the distribution of this "... more strictly pelagic ..." shark is salinity. Data available to them indicated that this animal was not found at salinities lower than about 35.5‰. They concluded that its offshore habit was at least in part caused by an avoidance of low salinities. Thus they explained the absence of the white-tip

along the east coast of the United States in summer where it might be expected on the basis of temperature alone.

Our records show that the white-tip occurs over a wide range of salinities. In 29°N, 88°W, for instance, where we have many records for July and August, the salinity may be lower than 28‰ (Dept. of Oceanography, A & M College of Texas, 1954). Furthermore, on the basis of salinity we cannot explain the absence of the white-tip from the northern and western side of the Gulf Stream in its passage through the Straits of Florida and northward along the Florida coast past the Bahamas (where the salinity is high). The area from Key West to off Palm Beach, Florida, was fished extensively by commercial shark fishermen from 1935 to 1949 using bottom set lines. Although the white-tip is apparently not available to bottom lines, regular trails of offshore fishing using floating lines were carried on. The only record of capture of a white-tip by a commercial boat was from the eastern side of the Gulf Stream near Bimini. We have caught the white-tip from early June to late October north of Cape Hatteras and west of the Gulf Stream. While we have not fished much in this region during the cold season, it seems probable that the white-tip withdraws to the south and east at this time. We have noted a withdrawal from the northern Gulf of Mexico when the waters there were cool. This may begin as early as December. In 1955 the most noticeable change in the shark fauna here occurred about 1 February. Sea surface temperatures at this time in the northern Gulf (over water deeper than 100 fathoms) are in the neighbourhood of 70°F (FUGLISTER, 1947). The withdrawal of the white-tip is accompanied by an offshore movement of some of the larger inshore sharks, notably *Galeocerdo cuvier* (Lesueur) the tiger shark, and several species of *Eulamia*.

Our records show that white-tips are ordinarily present in the surface waters where depths exceed 100 fathoms, but that they occasionally move into the adjacent shallower water. We suggest that the controlling factor is competition for food with other species of sharks which places the relatively slow-moving white-tip at a disadvantage.

The northernmost record for the white-tip in the western Atlantic, so far as we know, is for one taken in 40° 43'N, 66° 39'W on 25 July, 1953 (Fig. 2). SCHUCK and CLARK (1951) report a specimen taken in 40° 40'N, 57° 02'W on 12 June, 1950.

It has been generally supposed that the blue shark (*Prionace glauca*) is the abundant, widely-distributed, warm-water, oceanic shark. While gathering our white-tip records (Fig. 2) only one blue shark (a male, 295 cm, from between Santiago and Cabo Cruz, Cuba, 19° 30'N, 76° 50'W on 25 April, 1955) was seen by us in the area of the chart south of latitude 32°N. Published records within this area as given by BIGELOW and SCHROEDER (1948) include one each for St. Thomas, Cuba, and Miami, although HOWELL-RIVERO reported it as often seen around Cuba (in a personal communication also cited by BIGELOW and SCHROEDER). MATHER and DAY (1954) reported only 2 blue sharks (as compared with about 30 white-tips) in the wide area of the southern North Atlantic for which they had observations. This raises the point as to what the source is in the North Atlantic from which male blue sharks invade the waters off our northeast coast in such abundance in the summer.

SIZE

Very few sharks over about 250 cm or under about 150 cm in total length were caught. Since white-tips are born at a length of about 65-75 cm (BIGELOW and

SCHROEDER, 1948) it is apparent that we have not sampled a large part of the population (75-150 cm in length) (Fig. 3). It might be argued that our hooks are too large to catch the smaller sizes, but we discount this since we have caught small specimens of other species. Furthermore, it is certain that we would see the smaller sizes swimming about the vessel and nosing the baits if they were present. A young white-tip 102 cm in total length was taken near Tampico, Mexico, in late January from a long line set near the surface where the water depth was 1,200 fathoms. No

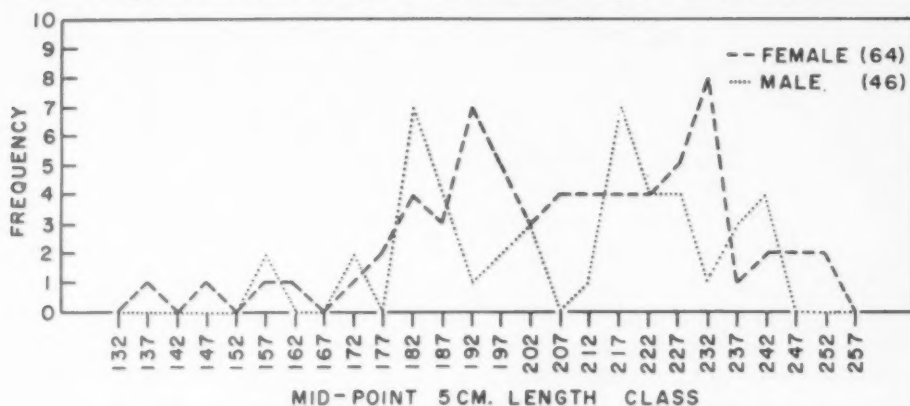


Fig. 3. Length-frequency distribution of a sample of white-tip sharks.

long line fishing was carried on south of this point during the winter or early spring. Some other carcharhinids (e.g. *Negaprion brevirostris*, the sub-tropical lemon shark) resort to restricted nursery areas to bear young. It is possible that we would have taken more specimens in the 75-150 cm size if we had fished in the southerly parts of the species' range in the fall and early winter. The extremely rapid growth of sharks in warm-water nursery areas may well explain the absence of specimens of this size in our collections (made mostly in the spring and summer) as has been noted for *Negaprion*, (SPRINGER, 1950b).

The longest white-tip for which BIGELOW and SCHROEDER (1948) had exact measurements was 350 cm long. This is considerably longer than our longest specimen. BIGELOW and SCHROEDER write that 12 to 13 feet (365-395 cm) is considered the maximum size, but that it is probable that an even larger size may be attained. Our data are insufficient to establish the size range of the species. However, in connection with the extremely large specimens mentioned above, a condition parallel to that found in the great hammerhead shark (*Sphyrna tudes*) is suggested. Unpublished measurements by SPRINGER of a series of adult great hammerheads show that a small percentage of the females are very much larger than the bulk of the adult breeding population. This and other observations support the possibility that some of the extreme size records for sharks persistently referred to in the literature are valid but are based on abnormal individuals, apparently always females. A false idea of the abundance of such sharks becomes established because these individuals, though solitary, eventually wander out of normal ranges into shallow water where they are easily caught. Furthermore, the capture of especially large sharks excites so much interest that they receive a disproportionate amount of attention in the literature.

A male white-tip 204 cm long weighed 60-65 kg (135-145 lb).

FOOD

Eighty-eight white-tip stomachs have been examined. Forty-one of these contain food, although a number contained only a cephalopod beak or two. It is possible that cephalopod beaks resist digestion to a greater degree than anything else that the shark ordinarily eats. This may bias the following data: Cephalopoda - in 19 stomachs; fish - 20 (including blackfin tuna and another scombrid fish, barracuda, look-down (*Selene*), and a white marlin about 250 cm with no evidence that it had been taken from a long line); garbage - 13; sargassum and other seaweed (probably accidental) - 4; unidentified animal remains - 1; unidentified sea bird - 1; Crustacea - 1.

Only a few white-tips taken on tuna long lines are included above. In general the latter had empty stomachs or contained only tuna or bait used for the tuna. One stomach contained several pounds of oil.

BEHAVIOUR

White-tips almost always exhibit some suspicion of a baited hook. They generally make several passes at a bait before taking it. Between these passes they may swim away 50 to 100 yards. On 18 March, 1953, between captures (0915-1315) in the Windward Passage, there were about 6 white-tips around the vessel continuously. These were nosing baited hooks and would not take them although they immediately engulfed similar baits not on hooks.

Although white-tips exhibit a cautious approach to objects suspected of being edible they are remarkably persistent. A great deal of effort has been wasted by the crew of the *Oregon* in attempting to drive white-tips away from the vessel while long lines were being hauled. The long line is hauled as the vessel moves slowly forward and the line with the catch is taken over the side. A few white-tips usually gather within ten to fifty feet of the stern but swim forward and downward at the approach of a hooked tuna. The tuna come from ten or more fathoms and are not visible from the vessel when the sharks seem to detect their presence. The sharks meet the tuna more than thirty feet from the vessel and get one or more bites before the tuna can be landed. White-tips are commonly caught on the long lines and may occasionally attack spent or dying tuna on the lines before they are hauled. However, more of the shark damage well below the surface in the Gulf of Mexico results from attacks by silk sharks (*Eulamia floridana*), mako sharks (*Isurus oxyrinchus*), and occasionally by other species of *Eulamia*. All of these sharks are numerous enough to be a serious problem for tuna fishermen. We have not seen the mako sharks at the surface except when they come up on a hook or hanging onto a tuna, but silk sharks in the Gulf of Mexico are often numerous when sets are made near the continental shelf and permit comparative observations. The silk sharks are less bold than the white-tips but are much faster. Consequently, if baits are being thrown overboard in large quantities when both species are present, the white-tips get most of the baits close to the boat but the silk sharks get all of those that sink rapidly or drift some distance from the vessel. Several times we have seen a silk shark and a white-tip of about equal size in competition for the same discarded fish. If the white-tip was close enough, it got the fish by driving the silk shark away.

The white-tip does not leap when hooked and puts up a relatively feeble resistance to capture. In this respect it is comparable to the blue shark. The silk shark shows

much more speed and power than a white-tip, but once on deck the latter is more troublesome. On a few occasions white-tips have been observed to be capable of at least short bursts of speed. We have attempted to use a type of firecracker, generally known as a cherry-bomb, to drive sharks away from the vessel. The cherry-bomb was put inside a fish, the fuse lit, and the assembly tossed overboard. Due to the deliberate appraisal of the bait by the white-tip this was not often successful. The premature explosion merely caused the shark to move off a few feet, than to resume its patrol. On one occasion, however, a white-tip picked up a fish with a slow fuse and the bomb exploded in its mouth. Smoke and bits of fish blew out of its gill openings, and the shark exhibited a creditable speed in moving away.

Recently, six or seven white-tips were around the *Oregon* as long line-caught white-tips were being killed and thrown overboard. The dying specimens were never attacked although as they sank they were followed out of sight by other white-tips. Even floating livers were untouched. This reaction to livers is not typical however, as we have often used them as bait on hand lines to catch other white-tips.

When white-tips swallow objects immediately at the surface the top part of the head is lifted well out of water. On one occasion when one of us was dangling a bait in front of a shark hard by the vessel's side it made many attempts to swallow the bait before it succeeded. Such exhibitions of clumsiness make one wonder how this animal can capture live fish and cephalopods and how one (which we identified from portions of its teeth) could strike a plastic encased instrument which was being towed at night at a speed of several knots. We might say in this connection that white-tips appear to be equally active by day and night.

SEXUAL SEGREGATION

Two types of sexual segregation are known in sharks. A "behavioural" type is exemplified by the tendency of individuals of the spiny dogfish (*Squalus acanthias*) to school with others of like size, the species sorting into aggregations of large mature females; mature males of medium size; immature females of medium size; or small fish of both sexes (FORD, 1921). That a given school tends to be of one sex had been noted by earlier authors (MEYER, 1875; SMITT, 1895; and BORCEA, 1906).

FORD also described what can be called "geographical" segregation in the rough-dog (*Scyliorhinus caniculus*). Several thousand specimens examined at Plymouth showed that males predominated in the winter (a peak predominance of about 65%) while females predominated in the summer (a peak of about 58%).

Geographical segregation was described by RIPLEY (1946) for the soupfin shark (*Galeorhinus zyopterus*). He showed that the sexes were generally unequally represented as a function of area or of depth in four California fishing areas. That this phenomenon exists in the blue shark (*Prionace glauca*) is indicated by BIGELOW and SCHROEDER (1948) who in writing of summering fish off northeastern United States and Canada say, "... few, if any, females take part in this yearly incursion ..."

We have some information showing that geographical sexual segregation is also a feature of the life history of the white-tip. In an area in the northern Gulf of Mexico whose radius is about 75 miles, 13 females and 3 males were caught during 13-30 August, 1954. A similar ratio (74 females to 15 males) was found in the same area during 10-26 August, 1955. In an area between Cuba, Hispaniola, and Jamaica with a radius of about 90 miles, 15 white-tips were caught during 18 March - 2 April,

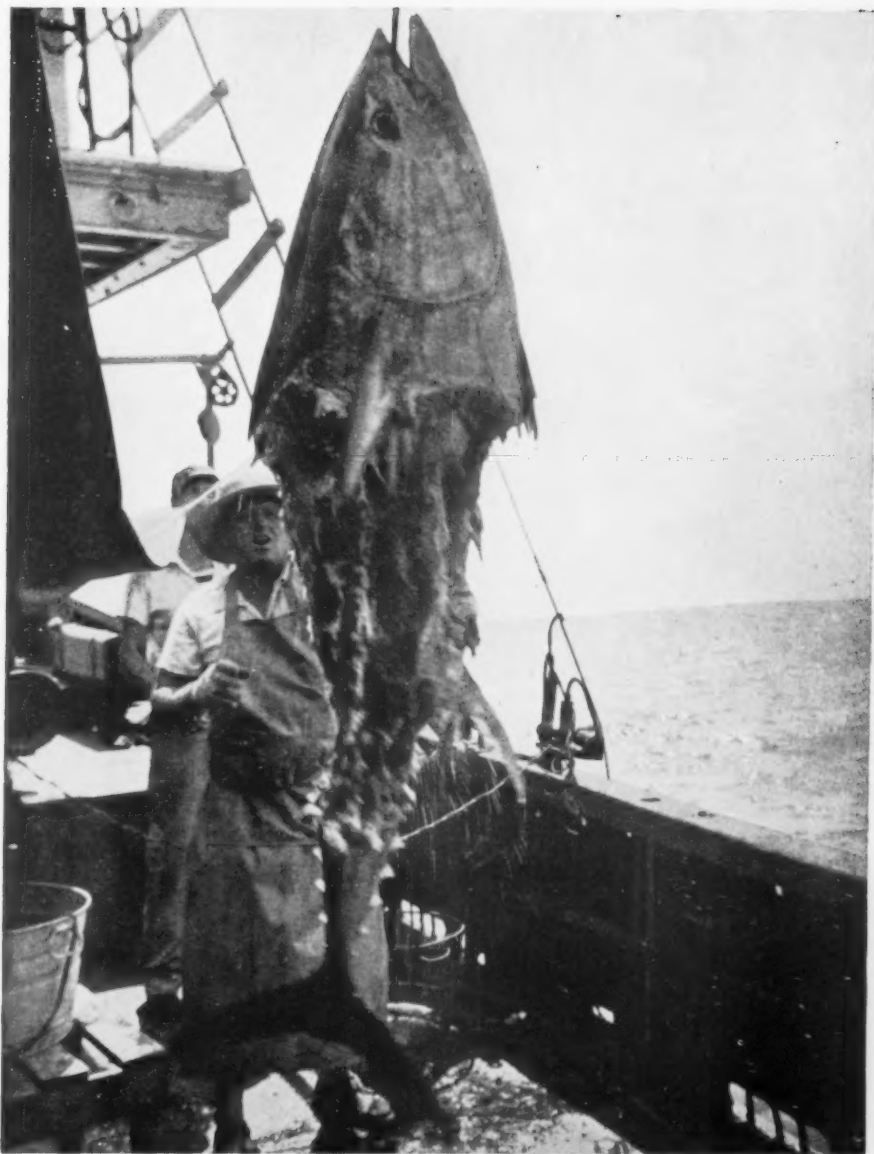


Fig. 4. Long line-caught bluefin tuna showing damage by white-tip sharks. This tuna weighed about 500 pounds before being attacked. Photo by ARNOLD.

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1953, 14 being males. In an area of about 80 miles in radius north and east of Puerto Rico 24 females and 7 males were caught during 23 February – 12 March, 1954 (see Fig. 2).

The geographical segregation phenomenon is not understood, but may be related to the existence of favoured pupping areas in which females tend to congregate seasonally.

REPRODUCTION

The fragmentary data available (Table 1, Fig. 5), suggest that both mating and pupping take place in the late spring or early summer and that the gestation period is about one year.

Table 1.

Locality	Date	Number of litters	Total number of specimens	Approx. mean total length	Authority
Northeastern Gulf of Mexico	13 Aug., 1951	1	7	150	BACKUS, SPRINGER and ARNOLD
Northern Gulf of Mexico	14–16 Aug., 1951	2	16	65	„
Northern Gulf of Mexico	26–28 Aug., 1951	2	14	160	„
38° 25'N, 68° 07'W	24 Sept., 1955	1	4	240	„
Central Gulf of Mexico	15 Dec., 1954	1	4	410	„
Northern Gulf of Mexico	13 Jan., 1955	1	4	465	„
North of Puerto Rico	23 Feb.–1 Mar., 1954	6	33	440	„
Trinidad Islet (20°S, 29°W)	8 April, 1913	1	1	670	NICHOLS and MURPHY (1914)
28° 40'N, 78° 46'W	3 May, 1886	1	5	520	U.S. National Museum (courtesy L. P. SCHULTZ)

We have noted two conditions of the oviducts in females without pups. In some females (generally the smaller ones) the oviducts are approximately circular in cross-section and about 10–15 mm in diameter. The oviducts are hard and the lumen is not very evident. The oviduct is held close to the dorsal wall of the body cavity by a narrow mesentery. Females in this category, which we presume are nulliparous, measured 173, 180, 189, 192, 198 and 198 cm ($\bar{x} = 188.3$) during 23 February – 23 March, 1954 (the only period during which we have made this type of observation).

In other females (generally the larger ones) the oviducts are flattened and measure about 30–40 mm from edge to edge. They are soft and limp, and the lumen is conspicuous. The oviduct lies loosely in the body cavity suspended by a wide mesentery. We presume these females to have previously borne young. During

23 February – 23 March, 1954, such females measured 192, 209, 215, 216, 221, 230, 232, and 246 cm ($\bar{x} = 221.2$).

Females with pups measured during this same period were 189, 205, 207, 212, 225, and 241 cm ($\bar{x} = 213.2$).

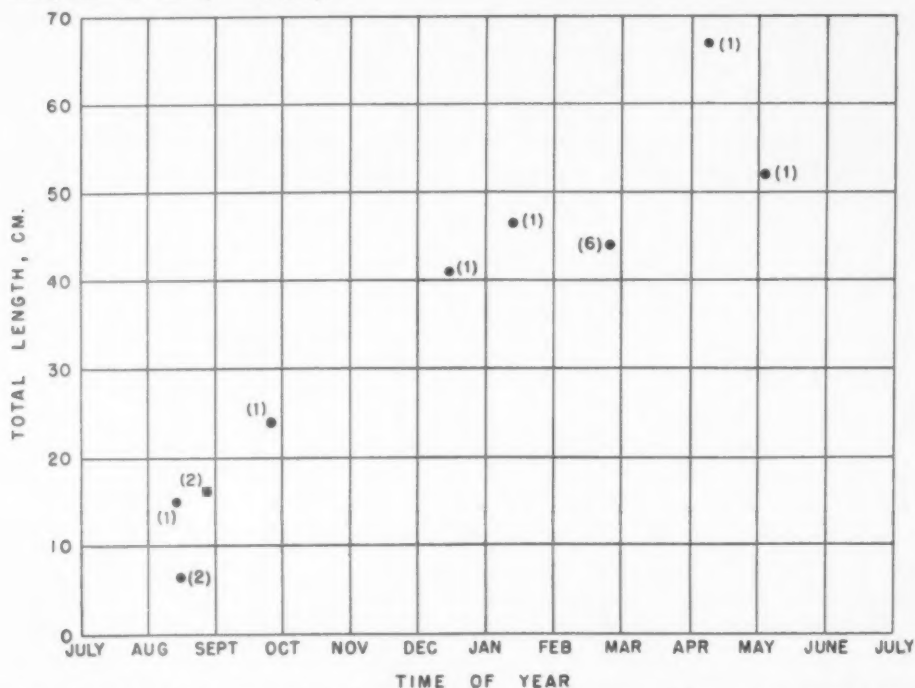


Fig. 5. Relationship between average length of embryos and time of year. The number in parentheses by each point indicates the number of litters used in arriving at the mean length.

Our original interpretation of the stretched oviducts was that females possessing them had recently dropped young. But since pregnant females at the same time were all carrying pups much smaller than the known maximum size, we no longer favour this notion. Moreover, females with stretched oviducts had large ovarian eggs measuring 25–45 mm in diameter (except one with very small eggs), while pup-bearing females had much smaller eggs (the largest being 10–15 mm in diameter). This suggests the possibility that females with stretched oviducts at this season are those that bore young the previous summer and that will mate again in the coming summer. We presume that pregnant females (with small eggs) would not mate during the coming summer.

The nulliparous females were of such a size that they could be expected to mate during the coming summer. Some of them bore ovarian eggs 10–15 mm in diameter, but some had very small eggs. None had eggs comparable in size to those of the larger non-pregnant females.

There is a good correlation (Fig. 6) between the length of the mother and the number of pups she bears; the greater the length, the greater the number of pups. The number of pups per litter in our series (15 litters) varies from 2 to 9 with an average of about 6.

In one litter of 9, 8 embryos measured from 495 mm to 595 mm, while the ninth measured only 240 mm. It was noted that the pseudoplacental connection was lacking between the small specimen and the mother.

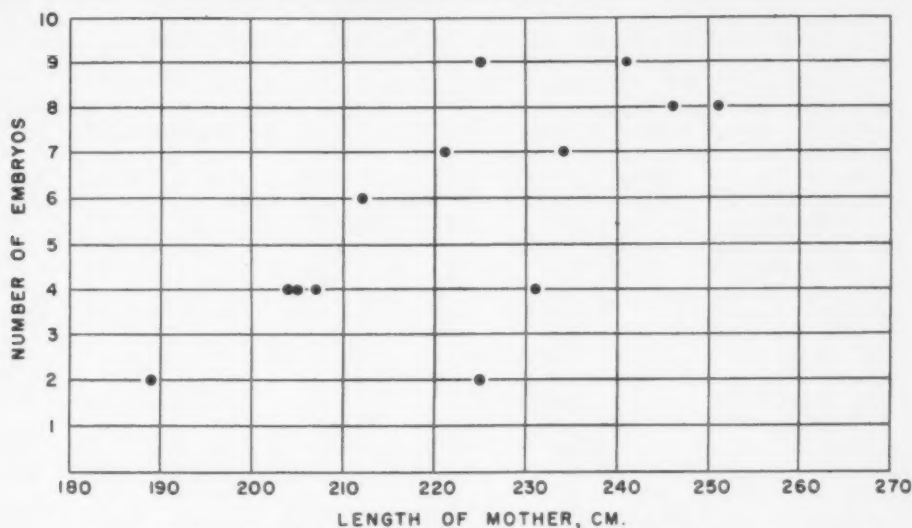


Fig. 6. Relationship between length of mother and the number of young she bears.

ANIMAL ASSOCIATES

One to 3 shark suckers (*Remora remora*) are generally attached to white-tips. They adhere so persistently that they are taken with the shark unless scraped off as the latter is pulled in over the rail. We have frequently seen them adjust their position on the shark with a rapid wriggling motion while the latter was being boated.

Often 1 or 2 pilotfish, *Naucrates ductor*, are in company with the white-tip (see Fig. 1). They generally swim a little above and behind the shark's first dorsal fin. They swim nervously back and forth near the shark after the latter has been hooked.

On several occasions we have seen one or several dolphins (*Coryphaena hippurus*) (8-10 on one occasion) swimming with the shark. They are generally to the rear or one side of the shark and by no means follow his movements as closely as the shark pilot. SCHUCK and CLARK (1951) in reporting their capture of a white-tip wrote that the stomach contained a dolphin, and they speculate as to the condition of the dolphin when captured. They also report the absence of dolphins in the immediate area of the capture of the shark, the implication being that dolphins avoid the latter.

A copepod parasite (or parasites) which is superficially attached to the white-tip's skin is frequent and often numerous.

Acknowledgements—We are indebted to Capt. W. SCOTT BRAY, First Mate A. D. COLBURN, Boatswain CARL SPEIGHT, former Radioman THOMAS LYON and many seamen of the R/V *Atlantis* for help in gathering many of the shark records.

Dr. H. B. BIGELOW, Mr. W. C. SCHROEDER, Mr. W. E. SCHEVILL, and Mr. MALCOLM S. GORDON read and helpfully criticized the manuscript.

REFERENCES

- BIGELOW, H. B. and SCHROEDER, W. C. (1948), Sharks. Fishes of the western North Atlantic. Pt. 1. *Mem. Sears Found. Mar. Res.*, **1**, 59-576, 100 figs.
- BORCEA, I. (1906), Recherches sur le système uro-génital des Elasmobranches. *Arch. Zool. expér. et gén.*, (4), **4**, 205.
- BULLIS, H. R., Jr. (1955), Preliminary report on exploratory long-line fishing for tuna in the Gulf of Mexico and the Caribbean Sea. Pt. 1. Exploratory tuna fishing by the *Oregon*. *Comm. Fish. Rev.*, **17** (10), 1-15, 25 figs.
- DEPARTMENT OF OCEANOGRAPHY, A. and M. COLLEGE OF TEXAS (1954), Oceanographic survey of the Gulf of Mexico. *Ann. Rept.*, 30 June, 1953 - 30 June, 1954, 1-14, 7 figs. (Unpublished manuscript).
- DODERLEIN, L. (1881), *Manuale Ittiologico del Mediterraneo*, Palermo, **2**, 40.
- FORD, E. (1921), A contribution to our knowledge of the life-histories of the dogfishes landed at Plymouth. *J. Mar. Biol. Assoc.*, N. S., **12** (3), 468-505.
- FUGLISTER, F. (1947), Average monthly sea surface temperatures of the western North Atlantic. *Pap. Phys. Ocean. Meteor.*, **10** (2), 1-25.
- GÜNTHER, ALBERT (1870), *Catalogue of the fishes in the British Museum*, **8**, 372.
- MATHER, F. J. and DAY, C. G. (1954), Observations of pelagic fishes of the tropical Atlantic. *Copeia*, (3), 179-188, 2 pls., 1 fig.
- MAUL, G. E. (1955), Five species of rare sharks new for Madeira including two new to science. *Not. Nat. Acad. Nat. Sci. Phila.*, **279**, 1-13.
- MEYER, F. (1875), Beitrag zur Anatomie des Urogenital-systems der Selachier und Amphibien. *Stizungber. Naturf. Ges.*, Leipzig, **2**, 38-44.
- MÜLLER, J. and HENLE, J. (1841), *Systematische Beschreibung der Plagiostomen*. Berlin, p. 37.
- NICHOLS, J. T. and MURPHY, R. C. (1914), Fishes from South Trinidad Islet. *Bull. Amer. Mus. Nat. Hist.*, **33**, 262.
- RIPLEY, W. E. (1946), The soup fin shark and the fishery. *Bur. Mar. Fishes, Div. Fish and Game, State of Calif., Fish Bull.*, **64**, 7-37, 17 figs.
- SCHUCK, H. A. and CLARK, J. R. (1951), Record of a white-tipped shark, *Carcharhinus longimanus*, from the western North Atlantic. *Copeia*, (2), 172.
- SMITT, F. A. (1895), *A History of Scandinavian Fishes*, (2), 1161.
- SPRINGER, S. (1950a), A revision of North American sharks allied to the genus *Carcharhinus*. *Amer. Mus. Novit.*, 1451, 1-13.
- SPRINGER, S. (1950b), Natural history notes on the lemon shark, *Negaprion brevirostris*. *Texas J. Sci.*, **2** (3), 349-357.
- SPRINGER, S. (1951), Correction for "A revision of North American sharks allied to the genus *Carcharhinus*." *Copeia*, (3), 244.
- TORTONESE, E. (1951), Ulteriori considerazioni sulle specie Mediterranee dei generi *Sphyrna* e *Carcharhinus*. *Doriana*, **1** (20), 1-8.

Measurements of illumination at great depths and at night in the Atlantic Ocean by means of a new bathyphotometer

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Abstract—The bathyphotometer described is a combination of a light-meter employing a photo-multiplier tube and a depthmeter employing a bourdon tube. The spectral sensitivity of the instrument extends approximately from 320 m μ to 650 m μ with a maximum at 480 m μ . Illumination as low as 10^{-7} μ w/cm² (about 10^{-12} of full sunlight) and depths as great as 610 m can be read directly on deck. The instrument thus permits the direct investigation of the light factor in the sea at depths and intensities far below those measurable by photovoltaic photometers.

Measurements of transparency made in the Florida Current off Miami gave extinction coefficients ranging from .031 to .056 for various strata between depths of 20 and 580 m. In the slope water about 200 miles SE of New York extinction coefficients of .062 to .072 were obtained for the upper 90 m and of .032 to .041 for layers extending to 596 m. These results, together with previous meagre information, indicate a uniform and high transparency for the water between 100 m and 600 m.

Measurements made at night in both localities showed that the illumination decreased with depth in the upper layers at about the same rate as during the day. Flashes of light, presumably from luminescent animals, were observed, particularly in the lower strata. At depths greater than 300 m the background light remained about constant or tended to increase. In one instance the general illumination at night at 600 m was about as great as during the day with individual flashes almost one thousand times greater.

INTRODUCTION

THE penetration of light into natural waters is of vital concern not only for the growth of green plants but also for the photic reactions of animals. In addition, a knowledge of transparency has many practical applications. Previous measurements of illumination in natural waters have provided us with considerable information on the intensity and quality of light in the upper water layers during the daytime, and the ecological significance of these has been summarized elsewhere (CLARKE, 1954). However, most of the instruments employed heretofore have been incapable of measuring accurately light weaker than 0.1% to 0.01% of full sunlight, and hence the observations have been limited to depths and times at which the natural illumination has exceeded this limit, or have depended on light from an artificial source.

Although the sensitivity of previous instruments is sufficient for investigating the growth of green plants, since photosynthesis generally requires about 1% of sunlight, earlier methods fell far short of measuring the minimum intensities of light significant for animals. Certain pond fish have been shown to be able to see small objects under an illumination of only 10^{-10} of sunlight, and this is also the approximate threshold of vision for man (CLARKE, 1936). Fish and other animals adapted to very deep water may be able to see in even weaker light. Certain animals find moonlight or starlight sufficient for vision, and the activities of many species are controlled by changes in light before sunrise or after sunset. A host of marine animals respond to the light from luminescent organisms; in some instances they may be attracted, in others repelled, or guided by a recognition of the pattern of light. For certain

species luminescence perhaps provides sufficient general illumination for vision, as will be discussed in a subsequent report (CLARKE and BACKUS, 1956). The minimum intensity of light which will affect photokinesis or phototaxis may be lower than the threshold for vision, and animals can undoubtedly respond to differences in light and shade, or day and night, at lower illuminations. The vertical migrations of plankton and of fish, which have become of special interest in relation to the movement of the deep scattering layers in the ocean, also occur at depths where the light is very weak (CLARKE and BACKUS, 1956).

Since all of the animal reactions mentioned above are affected by light intensities below the range of underwater photometers commonly used in previous investigations, a much more sensitive instrument was constructed in order to explore the problems involved as well as to add to our general knowledge of underwater optics. Previous discussions of possible light reactions in deep or turbid water, or during the dark part of the day, were based on extrapolations of shallow measurements under various assumptions as to the optical conditions in deeper layers.

The depth to which direct measurements can be made depends upon the type of photometer, the clarity of the water, and the intensity of the incident radiation. Underwater photometers employing photo-voltaic cells, such as the Weston photonic cell, are not serviceable for intensities much below $0.0005 \text{ g cal/cm}^2/\text{min}$ or $35 \mu\text{w/cm}^2$ (visible radiation). The energy of summer sunlight received on a horizontal surface at the Blue Hill Observatory, Boston, Mass., reaches a maximum of about $1.6 \text{ g cal/cm}^2/\text{min}$ or $112,000 \mu\text{w/cm}^2$ for total radiation, or about $0.75 \text{ g cal/cm}^2/\text{min}$ or $53,000 \mu\text{w/cm}^2$ for visible radiation. This is approximately equivalent to a light intensity of 11,000 ft. can. (HAND, 1937). Since the surface layers of the clearest ocean water cause a reduction in light of approximately ten fold for each 50 m of depth, as shown by earlier measurements, it is understandable that photonic cell photometers could not be used at depths greater than about 200 m under the best of circumstances.

Greater sensitivity and hence greater depth range has been attained by using photographic methods, but these are slow and are objectionable both because of the ship's time consumed and because changes in daylight and other conditions take place during the long period of exposure. JERLOV and KOCZY (1951) was able to carry out only a few measurements at depths greater than 200 m with a deep-sea camera. Their deepest measurement at 500 m made in the extremely clear water of the Sargasso Sea required an exposure of 2 h.

To satisfy the need for great sensitivity together with a rapid response, a photometer was designed which contains a photomultiplier tube and is capable of measuring intensities ranging down to less than $10^{-7} \mu\text{w/cm}^2$ or about 10^{-12} of full sunlight. In most previous observations of light penetration the depth of the photometer has been calculated from the length of the supporting cable and the wire angle at the surface. Since this procedure becomes unreliable at depths greater than 200 m, a depth meter was attached to the photometer head and the unit provided with insulated leads running to a deck unit where direct simultaneous readings could be made of the depth of the photometer and the light intensity at that depth. The combined instrument, termed the bathyphotometer, and measurements made with it in the Atlantic Ocean, are described below.

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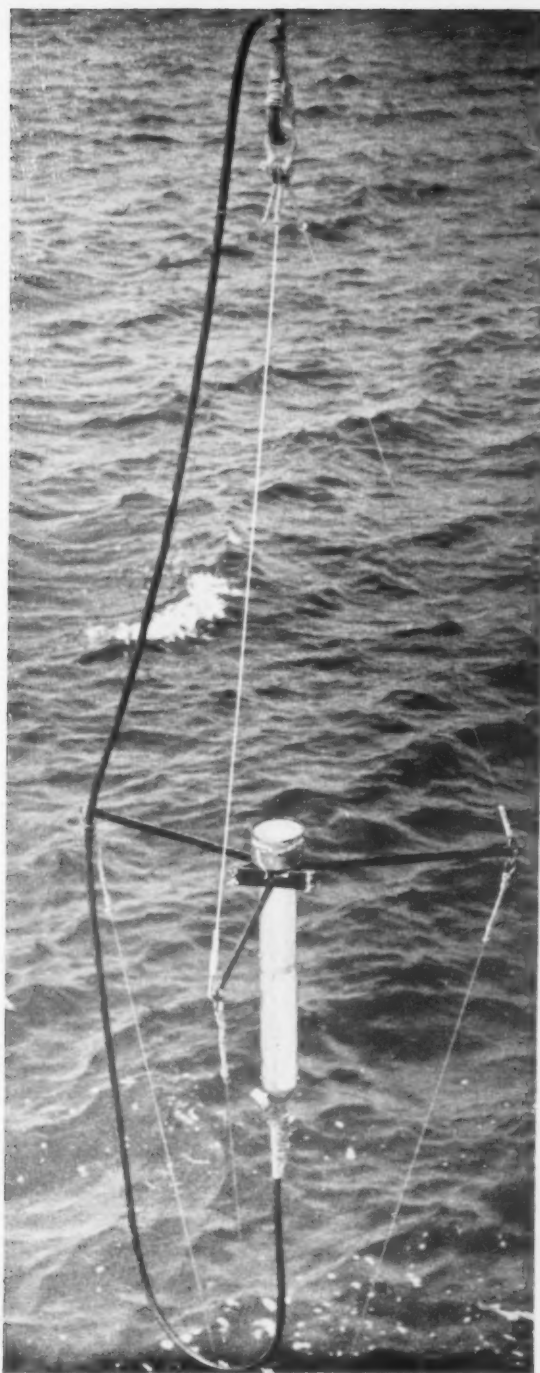


Fig. 1. Submerged unit before lowering. The hood for near-surface measurements has been placed over the photometer head. A 50 kg cylindrical lead weight was hung below the photometer.

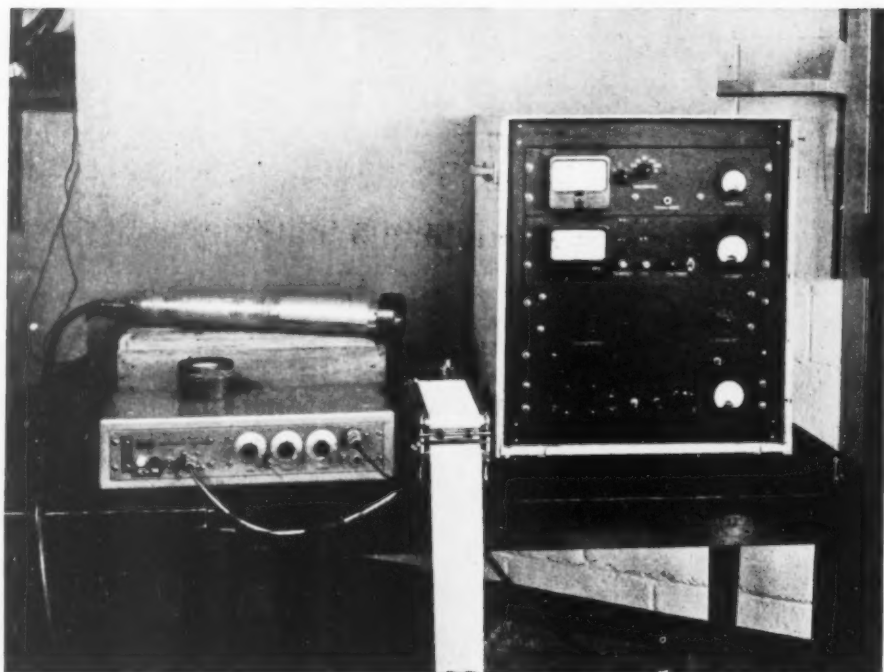


Fig. 2. Deck unit (right) showing microammeter for measuring light and depth, Brush recorder (centre) with Edin oscillograph amplifier (left) and submerged unit (rear) with hood removed.

DESCRIPTION OF BATHYPHOTOMETER

The bathyphotometer consists of two basic elements: a submerged unit (Fig. 1) carrying the photomultiplier tube and the depthmeter sensing element, and a deck unit (Fig. 2) consisting primarily of a high-voltage supply, a depthmeter indicator, and a vacuum tube microammeter. Supplementary equipment includes an Edin oscillograph amplifier and Brush recorder, on which flashes of light from luminescent animals can be recorded, and a field calibration unit. The size of the submerged unit has been kept small to reduce the drag and tilt of the instrument when lowered into water moving relative to the ship, and to enable it to be lowered on its own power-signal cable. The case is designed to operate to a depth of 750 metres.

The use of photomultiplier tubes to extend the range of underwater light measurements introduces a number of new considerations. Photronic cells are directly connected to a low impedance microammeter, or galvanometer, and have a stable, though low, sensitivity. Photomultiplier tubes, on the other hand, have remarkably high sensitivity, but possess certain inherent disadvantages. The tubes require a high supply voltage, of the order of 1,000 volts, and produce a signal current which ranges from 0.1 microampere to 1 milliampere. The output at constant light level is strongly dependent on the supply voltage so that a well-regulated power source is necessary. The signal at constant light level and constant voltage is also a function of the orientation of the tube in the earth's magnetic field, and hence requires magnetic shielding.

Further difficulty arises from the fact that both the 1,000-volt supply and the small signal current must pass through the same cable and connectors. It has been found, however, that the use of shielded leads and guard rings will maintain adequately low leakage to the signal wire.

The spectral response of photomultiplier tubes, unlike that of the photronic cell, is not similar to the standard luminosity curve for the human eye; so that direct readings of illuminance, if desired, can only be obtained through the use of filters with attendant loss of sensitivity. However, the spectral response of certain photomultiplier tubes has a broad maximum in the region of transmission of sea water, so that they may be employed for measurements of energy flux under suitable conditions.

Photometer. The photometer utilizes the linearity of the current response of photomultiplier tubes operated at constant supply voltage to obtain an extended scale of inherently higher precision than can be obtained by operating at constant anode current (SWEET, 1946; KAMPA and BODEN, 1954). The photometer circuit comprises a high-voltage supply, the phototube, and the vacuum tube microammeter (Fig. 3).

The high-voltage supply utilizes a chain of special Amperex 0G3 regulator tubes, characterized by stability and low drain, and allows selection of the high voltage in steps of 83 volts, which is the operating voltage of a single 0G3. Line voltage fluctuations at the input to the supply are controlled manually since line frequency instability on board ship makes the use of constant voltage transformers unreliable. In the absence of input voltage control fractional output voltage fluctuations are 1/50 of the fractional input voltage fluctuations.

An end window phototube is used for compactness and improved light collection geometry. An RCA 5819 was selected because of its favourable spectral response, which is high and relatively broad in the region of maximum transmission of sea water (Fig. 4). Its 3.75 cm diameter photocathode presents a large, well exposed area for the collection of light. The supply voltage required by this tube is lower than that of other similar types. It is protected against the earth's magnetic field by a Mu-metal shield.

The output of the phototube anode is brought to the deck unit by a shielded cable, and is there measured by a vacuum tube microammeter in which the various ranges are obtained by switching precision load resistors across the current to be measured.

Depthmeter. The depthmeter and associated circuit are identical with those used with cable-suspended hydrophones and described by KNOTT (1953). The sensing element is a helical bourdon tube which drives a wire-wound potentiometer. The meter has a full-scale deflection equivalent to 610 m and depths can be read to within ± 2 m.

Cable. The cable used was specially designed for this application and was constructed by the Okonite Co. Four conductors were cabled around a central core of aircraft steel (rated breaking strength 216 kg), and the whole was covered with a natural rubber compound for low-temperature flexibility, giving an outside diameter of 1.5 cm. Two of the conductors are of No. 14 tinned copper, are unshielded, and carry the depthmeter signal. The other two conductors are of No. 18 tinned copper, are shielded with copper braid, and carry the high-voltage and phototube signal respectively.

The shields are used as ground return for the depthmeter and photometer and, being at ground potential, prevent leakage to the signal lead.

The total length of cable available was 760 m, and a vertical depth of slightly over 600 m was reached with the photometer in calm weather. The whole cable weighed 234 kg in air or about 100 kg in water, but a stress greater than the weight of the cable can be caused by the drift and roll of the ship. The effect of the latter was reduced by using 5 stands of 1.3 cm shock cord in the attachment of the block over which the cable was paid out. The breaking strength of a sample section of the cable was found to be about 338 kg in a laboratory test; at sea the cable was used at tensions up to 250 kg as measured by a Dillon dynamometer. The use of a multiconductor cable of this sort has the disadvantage of its bulk and weight in handling and its considerable drag in the water, but it provides the great advantage of allowing the voltage regulation and measurements of light and depth to be made directly and continuously in the deck laboratory.

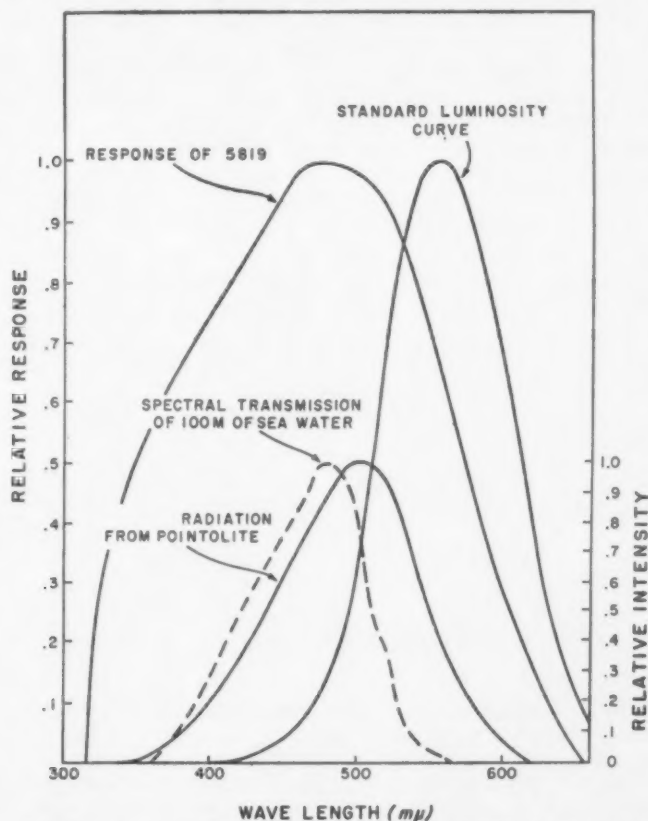


Fig. 4. Comparison of the response of R.C.A. photomultiplier cell 5819 with the standard luminosity curve (from the *Handbook of Chemistry and Physics*), the spectral transmission of the clearest sea water (CLARKE, 1939a), and the emission of the Point-o-lite lamp passing through Corning filter No. 4303.

Calibrating Unit. The calibrating unit consists of a 30 c/p "Point-o-Lite" bulb operated at 450 ma (Fig. 5) placed in a light-tight box at a distance of 37 cm from a door at one end into which the head of the photometer may be inserted. The radiation from the bulb is filtered through a Corning No. 4303 blue-green filter, yielding a computed irradiance of 12.5 microwatts/cm². This may be attenuated in known steps by interposing Kodak neutral density filters between the blue-green filter and the photometer head.

Calibration. A photometer will read in units of illuminance, independent of the spectral distribution of the incident light, only if the response of the detector is identical with the standard luminosity curve (Fig. 4). In underwater photometry it is not desirable to measure the flux of radiant energy in these terms, which reflect the sensitivity of the human eye and are not necessarily pertinent to marine organisms. The measured transmission of sea water extends below 400 millimicrons, a region where a device reading in units of illuminance would be insensitive.

Calibration in terms of energy flux is possible because of the broad maximum in the response of the photomultiplier tube in the region of transmission of sea water. The actual calibration in terms of irradiance in microwatts/cm² is made by exposing the instrument to a known amount of radiant energy whose spectral distribution is similar to that of submarine daylight. The calibration is valid for light which falls in the range from 400 to 580 millimicrons, and thus is appropriate for measurements in the subsurface layers of the ocean where the radiation is confined within these limits (CLARKE, 1954). For measurements near the surface allowance must be made for the fact that the photomultiplier tube is sensitive to longer wavelengths than those encountered in the deeper strata. Consequently, measurements with the bathyphotometer in the upper layers would be expected to yield a larger extinction coefficient than that obtained in the deeper layers, assuming that the water is homogeneous. Actually the value would not be expected to be much larger, because the spectral sensitivity of the photomultiplier tube cuts off rapidly. Since the bathyphotometer is relatively less sensitive than the Weston photonic cell to the longer wavelengths, the former would be expected to produce a somewhat smaller extinction coefficient than the latter in the upper strata of the same water body.

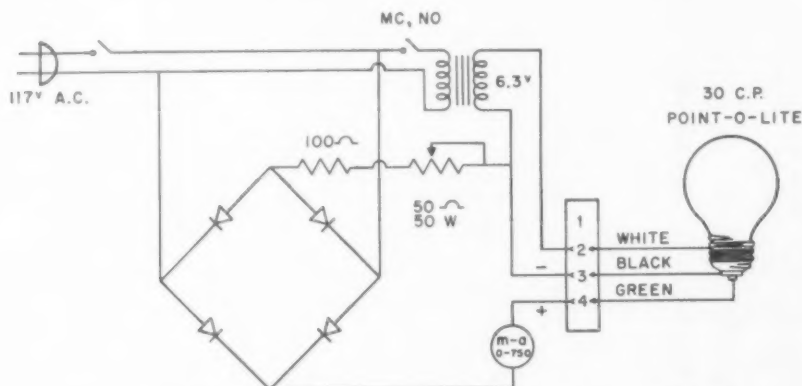


Fig. 5. Circuit for controlling the current supplied to the Point-o-lite lamp.

Since the linearity of the bathyphotometer has been demonstrated by careful laboratory calibration, it suffices in practice to establish one or two points on the calibration curve of current as a function of light intensity for each of the supply voltage used at sea.

Operating Limitations. The inherent linearity of the response of a photomultiplier tube is subject to two limitations. These are readily apparent in the complete calibration curves (Fig. 6). The nonlinearity at the high current level is due to the limited current flowing in the dynode voltage divider, and is not due to the tube itself. However, it serves as a safety device which prevents the anode rating of 750 μ A from being appreciably exceeded. For the sake of gain stability it is desirable not to exceed 500 μ A. Failure to observe the current rating of the anode may result in destruction of the tube, but long before this takes place fatigue of the last dynode stages will temporarily or permanently change the amplification of the photomultiplier tube (ENGSTROM, 1947).

In the practical use of the bathyphotometer the minimum light intensity which can be measured depends upon a minimal signal current which is significantly greater than the sum of the dark current and electrical leakage. During measurements at sea the dark current ranged between 0.01 and 0.04 μ A when using the highest supply voltage for greatest sensitivity. A direct test with the photometer head shielded from all light showed that the dark current was no greater when the cable was

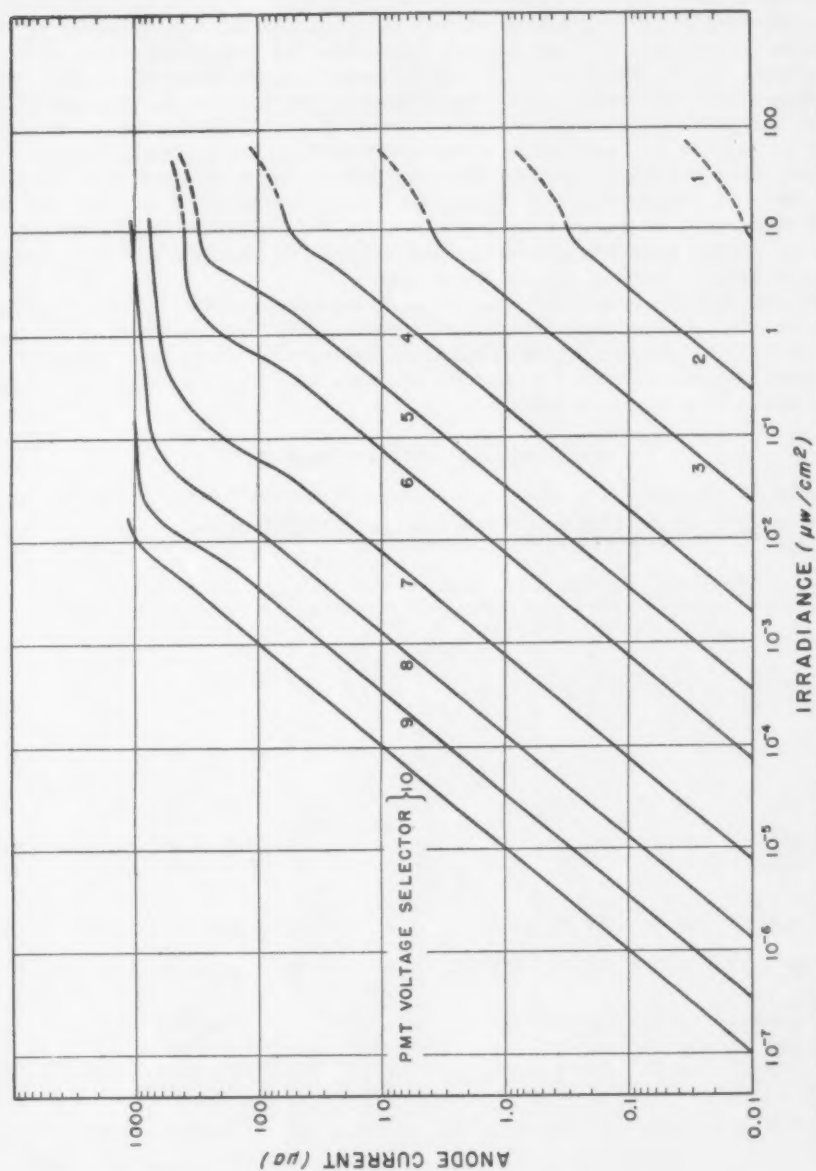


Fig. 6. Calibration curves for the bathyphotometer showing the relation between anode current and irradiance.

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lowered into the water to its entire length than when it was reeled up on deck. As a result of the low and relatively steady dark current, illumination was measurable to a minimum of about $10^{-7} \mu\text{w}/\text{cm}^2$.

The departure from linearity at high levels of illumination is caused by the internal resistance of the photocathode. It becomes noticeable when the illumination exceeds 3×10^{-4} of full sunlight. Consequently reliable readings of light of greater intensity than this cannot be made with the unprotected photometer. For measurements near the sea surface involving intensities extending up to full sunlight a hood containing a neutral filter of density 4 is placed over the photometer head. The filter is sealed between a disc of lucite below and a disc of No. 2254 Plexiglas above. The space between the lucite disc and the photometer head is filled with sea water to reduce reflection loss. This type of Plexiglas is a semi-translucent white material, equivalent to the opal glass used on older photometers. The Plexiglas disc forms the receiving surface of the hood and through its diffusing qualities minimizes the effect of solar angle, wave refraction, and photometer tilt. This arrangement follows the standard practice for the measurement of subsurface illumination (ATKINS, CLARKE, PETTERSSON, POOLE, UTTERBACK and ANGSTROM, 1938).

During observations at sea a record of changes in the radiation incident on the surface was kept by means of a deck photometer containing a Weston photronic cell. Suitable corrections were made in the calculations of transparency from the subsurface measurements. On the basis of the precision of the depth meter and lightmeter the values for the extinction coefficient obtained in this investigation are believed to be accurate to about 2%.

RESULTS OF MEASUREMENTS

One set of measurements with the bathyphotometer was made in the spring of 1955 at stations in the Florida Current located 10 and 40 miles off Miami, Florida,

Table 1. Summary of Measurements of Light Penetration.

Series	Date 1955	Latitude N	Longitude W	Bottom depth (metres)	Depth range for measurements (metres)	Extinction coefficient k^*	Time E.S.T.	Sky	Wind (miles/hr)
10	Mar. 4	25° 44'	79° 56'	311	20-75	.031	1100-1200	Clear	12
12	Mar. 31	25° 35'	79° 24'	777	75-152	.056			
13	Apr. 1	25° 35'	79° 24'	777	0-490	—	2000-2100	Halfmoon	18
					30-160	.043	0940-1040	Clear	12
					160-460	.034			
					460-580	.038			
20	July 18	38° 56'	70° 24'	3036	10-91	.072	1510-1715	Foggy	10
					91-427	.038			
21	July 19	38° 28'	68° 45'	3931	10-91	.072	1315-1545	Hazy	8
					91-363	.038			
					363-596	.041			
22	July 19	38° 25'	68° 48'	3950	0-610	—	2115-0030	Overcast	10
23	July 20	38° 24'	69° 10'	3840	0-290	—	1800-2035	Clear	8
24	July 21	38° 21'	69° 09'	3840	30-92	.062	1350-1530	Clear	12
					92-400	.039			
					400-554	.032			
25	July 21	38° 21'	69° 09'	3840	30-270	—	1725-1950	Clear	8

*Extinction coefficient = k in the equation $I/I_0 = e^{-kL}$ where light is reduced from I_0 to I by a stratum of water L metres thick.

and another set was made the following summer at stations located in the slope water about 200 miles SE of New York. The dates, positions, and other data relating to the measurements are summarized in Table 1 together with the values of the extinction

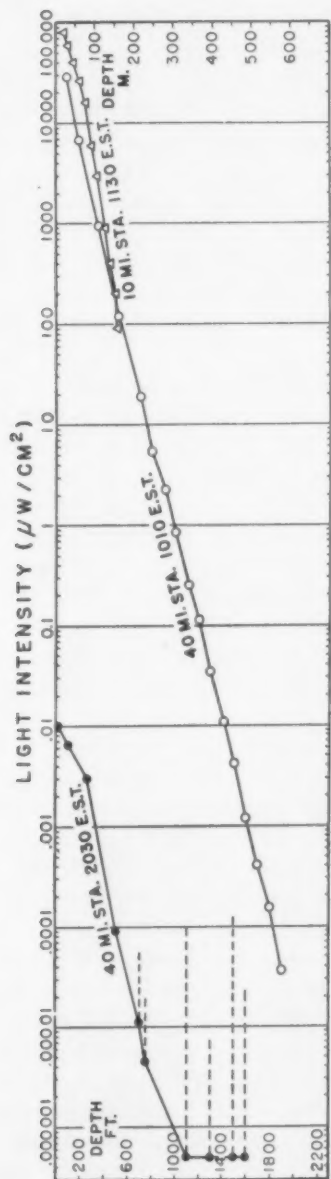


Fig. 7. Relation between depth and light intensity (logarithmic scale) at stations 10 miles off Miami (Series 10, Table 1) and 40 miles off Miami in daytime (Series 12) and at night (Series 13). Dashed lines indicate the approximate magnitude of flashes from luminescent animals.

coefficients for the indicated strata. Graphs of certain series of light penetration measurements are presented in Figs. 7 to 9. Details of the measurements made in relation to movements of deep scattering layers and in relation to luminescent flashes will be discussed separately (CLARKE and BACKUS, 1956).

Measurements in the Florida Current

Transparency. The station occupied 10 miles off Miami was located in the western part of the Florida Current (Gulf Stream) where the water is a variable mixture from several sources, including the Yucatan Channel and the Gulf of Mexico. Measurements with the Clarke marine photometer containing a Weston photronic cell gave an extinction coefficient of $k = .050$ on 4 March, 1955 for the water layer from 5 m to 25 m. MILLER, MOORE and KVAMMEN (1953) reported coefficients varying from $k = .041$ to $.075$ (with one observation of $k = .095$) for the surface stratum at the same station between August, 1950 and February, 1952, using the same type of photometer.

Our measurements on 4 March, 1955 with the bathyphotometer (Series 10) gave an even lower value for the extinction coefficient for the stratum from 20 m to 75 m ($k = .031$), but the value for the layers below 75 m was about the same as for the surface stratum. This indication of lower extinction values in the subsurface layer may be due to differences in the instruments, or a real difference in transparency may have existed. The observation of water clearer above 75 m than below that depth may be due to a direct and rapid movement of water at that level from the known clear water masses to the south (CLARKE, 1938), whereas the deeper strata may have been mixed with less clear water from the Gulf of Mexico. Further observations will be necessary to determine whether the factors suggested above are actually effective, or whether other causes underlie the differences in transparency observed.

The station 40 miles off Miami was located east of the swiftest part of the Florida Current and only a few miles west of Gun Cay and Cat Cay. The water here, derived from among the Bahaman Islands and the Sargasso Sea, is relatively homogeneous and changes little from season to season. On 1 April the temperature in the upper 100 m was between 24° and 25°C and decreased at a uniform rate to 7.6°C at 645 m. Our daytime measurements with the bathyphotometer (Series 13) gave an extinction coefficient of $k = .043$ for the stratum 30 to 160 m, and values varying from $k = .034$ to $.038$ down to 580 m. The water thus displayed a rather uniform transparency down to this great depth. The higher value for the extinction coefficient above 160 m may be due partly to the fact that the spectral sensitivity of the photometer includes the longer wavelengths which are absorbed rapidly in the upper strata. However, according to the calculations of JERLOV (1951) this selective action has little effect on the extinction coefficient at depths greater than 50 m in the clearest water. Since the graph for series 13 shows no noticeable change in slope down to 160 m., the lower transparency represented probably means that the water in this stratum had been modified more than the deeper water.

The transparency value for the stratum extending to 160 m may be compared with values obtained in neighbouring areas by CLARKE using photronic cells and by JERLOV using selenium rectifier photoelectric cells. Measurements by CLARKE (1938), in the Cayman Sea west of Jamaica, gave an extinction coefficient of $.045$ for the

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stratum 2 to 95 m and of .038 from 95 to 185 m. Values ranging from .039 to .049 for the upper 100 m were found at stations east of the Bahamas (CLARKE, 1941). Near the same area, using a photometer limited to the blue region of the spectrum (465 m μ), JERLOV (1951) obtained values of .041 to .043 for the stratum extending from 100 to 200 m. For the upper 100 m the extinction coefficient ranged from .028 to .039 for radiation limited to the blue region, but calculations showed that a value of about $k = .042$ would characterize the extinction for the whole spectrum for 25 to 100 m. Although the different sensitivities of the photometer used complicates the picture, it appears that the transparency of the water in the upper 200 m is generally uniform in the Caribbean region, and that our measurement on 1 April (Series 13) was representative.

Our measurements at deeper levels are the first that have been reported using direct reading photometers, but they may be compared with two measurements made with a deep-sea camera by JERLOV and KOCZY (1951) south of Bermuda. These investigators reported values of $k = .039$ and .038 for strata extending from the surface to 400 m and to 500 m respectively. These values agree very closely with our measurements, which extended to 580 m.

Observations at Night. Measurements were made during the night of 31 March (Series 12) at the same station as that at which the daylight observations were made on 1 April. During the period of measurement a half moon was shining and the ship's lights were extinguished. From Fig. 7 it will be observed that under these conditions the light at night at the surface was roughly 10^{-7} of that during the middle of the day. As the bathyphotometer was lowered into the water, the light intensity dropped off at about the same rate as it did during the day until a depth of 335 m was reached.

When the photometer was suspended at depths greater than 200 m, the light meter recorded large but very brief increases in current at irregular intervals. These are almost certainly to be interpreted as flashes of luminescence from deep sea fishes, crustaceans, or other animals. On this occasion the first flashes were observed at a depth of 212 m. They were relatively infrequent at this level but became much more frequent at greater depths, until below about 300 m flashing was practically continual.

The approximate intensities of the flashes as they reached the photometer are indicated by the extent of the broken horizontal lines. Between 200 and 300 m the magnitude of the flashes was only about two to five times as great as the illumination penetrating from the surface. At depths greater than 300 m there was no further detectable diminution of light in the water, presumably because the general illumination from bioluminescence had become greater than the light reaching these depths from the surface. The intensity of individual flashes of luminescence was more than 200 times the magnitude of the background illumination. The flashes may have been produced by animals with brilliant photophores at some distance from the bathyphotometer, or by animals producing weaker luminescence at closer range, either stationary or moving past. Indeed, in some instances the photometer or its bridle may have actually come in contact with passing animals and thereby caused a luminescent discharge.

During the daytime measurements at the same station on 1 April, the needle of the light meter dropped steadily without irregularities at all levels down to 580 m.

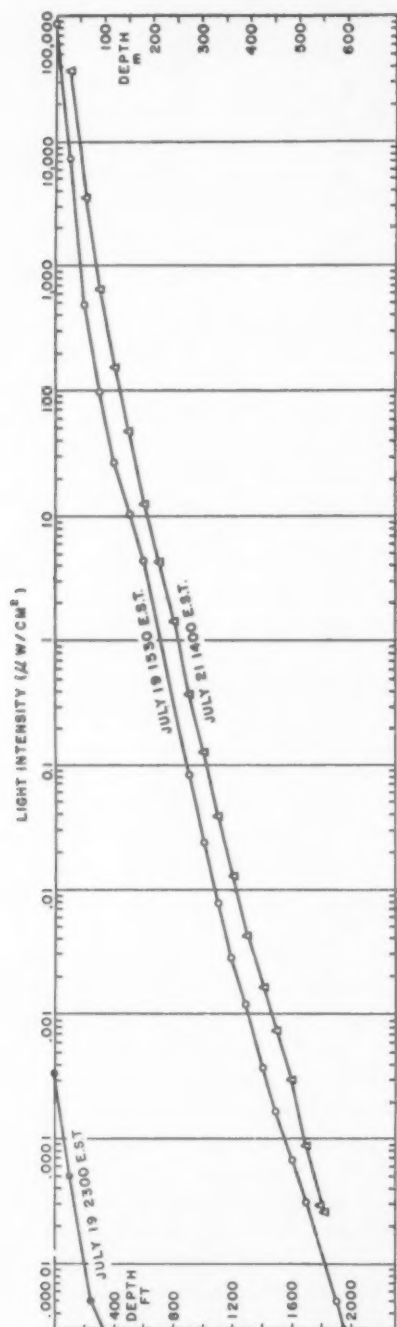


Fig. 8. Relation between depth and light intensity (logarithmic scale) at stations 200 miles S.E. of New York. The entire extent of daytime measurements on 19 July (Series 21) and on 21 July (Series 24) is shown, and the upper portion of nighttime measurements on 19 July (Series 22).

At this depth a few weak flashes were observed. Failure to observe flashes of luminescence at levels above this may have resulted from the fact that the higher intensity of illumination from the surface would render the animal light undetectable; but it may also have been due to a migration of luminescent animals to greater depths during the day, or to a diurnal rhythm involving the cessation of luminescent discharge in the day period. Further investigation will be necessary to settle these questions.

Measurements in the slope water

Transparency. Measurements were made in the slope water between the continental shelf and the northern edge of the Gulf Stream at stations located about 200 miles SE of New York. At these stations the temperature in the upper 15 metres was about 24°C and dropped uniformly to 13°C at 65 m. Below this the temperature remained roughly constant to 150 m and then dropped to 4.7°C at 600 m. This thermal structure shows the effect of seasonal warming and reflects the fact that the upper layers of the slope water have received admixtures of coastal water. Differences in the origin of the various strata of the slope water may be correlated with vertical differences in transparency. Our measurements made on 18 to 21 July (Series 20, 21 and 24) reveal a stratum about 90 m thick with a higher extinction coefficient ($k = .062$ to $.072$), overlying water considerably more transparent ($k = .032$ to $.041$) Table 1 and Fig. 8).

The transparency found for the upper stratum may be compared with earlier observations in this general region. Measurements were made throughout the year 1937-38 at Stations *A*, *B* and *C* located respectively in the coastal water, the slope water, and the Sargasso water on a line between Long Island, N.Y. and Bermuda (CLARKE, 1939b). Station *B* was located about 20 miles north of the location of our present Series 20, and yielded values ranging from $k = .050$ to $.10$ for the extinction coefficient. Our 18 July, 1955 value of $.072$ falls in the middle of this range. A measurement on 7 March, 1941 (CLARKE, 1941; Station 4174, Series 556) at a point about half way between our Series 20 and 21 and only about 20 miles from Series 24 gave an extinction coefficient of $.077$ for the upper 86 m, thus indicating close agreement with our present observations. At a station in the Gulf Stream about 50 miles south of our Series 21 and 24 occupied on 24 July, 1934, a value of $k = .049$ for the upper 140 m was obtained for wavelengths 490 to 620 $m\mu$, and of $k = .048$ for the upper 180 m for wavelengths 310 to 450 $m\mu$ (OSTER and CLARKE, 1935; Station 2245, Series 311 and 310). At station *C* farther to the southeast in the Sargasso water coefficients varied between $k = .042$ and $.066$ during 1937-38. Although these measurements are not entirely comparable because of differences in methods, a consistent change in transparency for the upper 100 m in this region is discernible from values averaging about $k = .08$ in the centre of the slope water to values of about $k = .05$ in the Sargasso water.

The much deeper extent of our present measurements makes it possible to compare the transparency of the upper stratum discussed above with the underlying water. The curves of light penetration for all three daytime series in this region show a change of slope at about 90 m. The underlying water down to about 400 m has an extinction coefficient of $k = .038$ or $.039$. The water below this was characterized by a slightly higher value ($k = .041$) in Series 21 and a somewhat lower value ($k = .032$) in series 24.

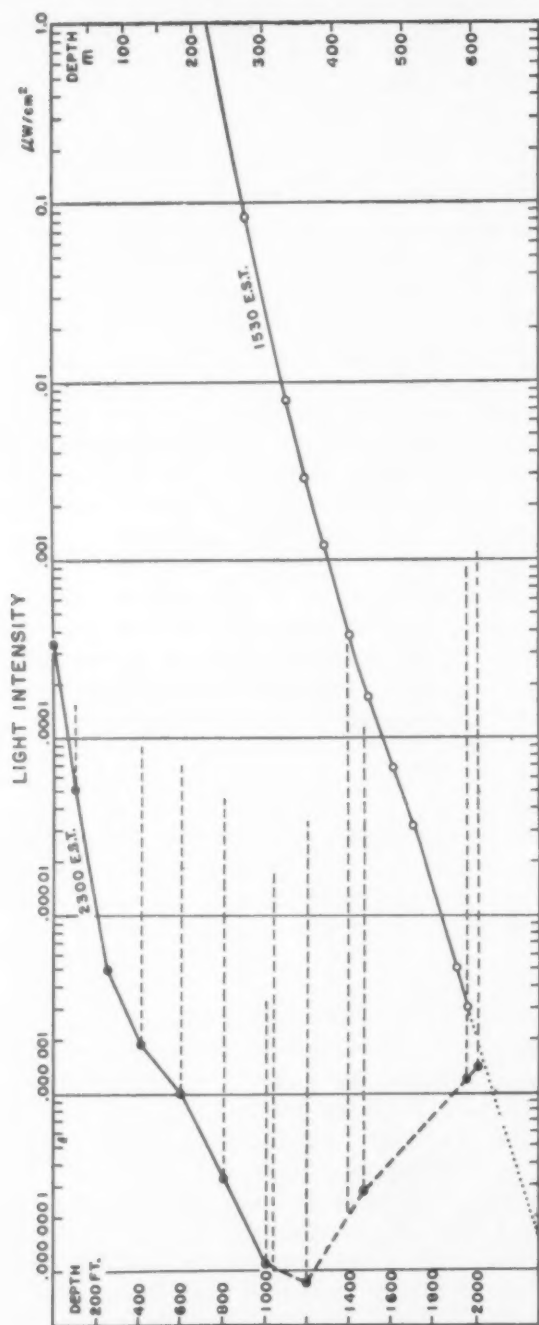


Fig. 9. The lower portion of daytime measurement (1530 E.S.T., Series 21) and entire extent of nighttime measurement (2300 E.S.T., Series 22) on 19 July at the same station 200 miles S.E. of New York. The dotted line is an extrapolation of the daytime curve assuming the same transparency. Dashed lines indicate the approximate magnitude of flashes from luminescent animals.

The only other deep measurements available for comparison with our observations in the slope water are our present Series 13 off Miami and the measurements of JERLOV (1951) and of JERLOV and KOCZY (1951) south of Bermuda – both in entirely different water masses and more than 800 miles away. Reference to Table 1 will show that the transparency of the deeper slope water is closely similar to that found off Miami. The value of JERLOV and KOCZY of $k = .041$ to $.043$ for the stratum from 100 to 200 m, obtained with a photo-electric photometer, and of $k = .039$ and $.038$ for strata extending to 500 m, obtained photographically, are also in close agreement with our results. In addition, three deep observations by these investigators in the Pacific Ocean near Tahiti produced nearly the same extinction coefficients. Our measurements thus add to the areas of the sea which have been found to have a remarkably uniform and similar transparency from 100 m down to 400 m or to 600 m. The question of whether this uniformity extends to yet greater depths and to all regions of the ocean must await further investigation.

Observations at Night. Night measurements were made beginning in the evening of 19 July and extending past midnight (indicated as 2300 E.S.T. in figures). The upper portion of the night curve is shown in Fig. 8, where it can be seen that the night illumination at the surface was somewhat less than 10^{-8} of the daytime illumination. The moon had not risen, the sky was lightly overcast, and all externally visible lights of the ship were extinguished. The lower part of the daytime curve and the entire extent of the night observations are shown in Fig. 9.

The night measurements showed a diminution of light with depth through the upper 75 m at about the same rate as was observed during the day. At greater depths the rate of extinction became less. A few flashes of light, presumably from luminescent animals, were observed at 30 m, and flashing became more frequent, though irregular, at increasing depths, as was the case in the night observations off Miami. Below about 300 m flashing had become so frequent that the background illumination could be determined only with difficulty, and is indicated by a continuation of the curve as a broken line. At depths greater than 360 m the background illumination definitely increased, until at 600 m there was just about as much light at night as during the day. The approximate magnitude of the larger, individual flashes of bioluminescence is indicated by the horizontal broken lines. A tendency for the brightest flashes to occur at the greater depths is apparent; some of these were 1,000 times the intensity of the background. During the daytime measurements occasional flashes, slightly above the background illumination, were noted (but not indicated on the figure) at about 400 m, and especially at depths greater than 460 m; but these were not sufficiently frequent to interfere with the determination of the background illumination. However, if the amount of luminescence during the day is the same, or greater, below 600 m, then the general illumination will not decrease, and may even increase. No doubt the intensity and the degree of irregularity in the illumination will be found to vary greatly at different depths and in different regions of the sea, according to the type and abundance of luminescent animals present.

Some information exists on the vertical and horizontal distribution of deep-sea animals possessing photophores or other means of producing luminescence, but up to the present we have had little knowledge of the quantity, quality, or periodicity of the light produced. Graphical records of variations in luminescence at levels above 500 m at night are given by CLARKE and BACKUS (1956). During his descent

in the bathysphere off Bermuda, BEEBE (1934) could see no daylight from the surface at depths greater than 520 to 580 m, but he reported the occurrence of brilliantly luminescent animals at all depths down to 920 m, where he states ; " the jet blackness of the water was broken only by sparks and flashes and steadily glowing lamps of appreciable diameter, varied in colour and of infinite variety as regards size and juxtaposition." The blackening of a photographic plate at a depth of 1,000 m in the vicinity of the Azores, reported by HELLAND-HANSEN (1912) and often referred to in the literature, may have been due in part to the light from passing luminescent animals. Methods are being considered for extending our light measurements to still greater depths, and for ascertaining the type, abundance, and activity of luminescent animals at deeper levels.

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REFERENCES

- ATKINS, W. R. G., CLARKE, G. L., PETTERSSON, H., POOLE, H. H., UTTERBACK, C. L. and ANGSTROM, A. (1938), Measurement of submarine daylight. *J. du Cons.*, **13**, 37-57.
- BEEBE, W. (1934), *Half Mile Down*. Harcourt Brace and Co., New York, 340 pp.
- CLARKE, G. L. (1936), On the depth at which fish can see. *Ecology*, **17**, 452-456.
- CLARKE, G. L. (1938), Light penetration in the Caribbean Sea and in the Gulf of Mexico. *J. Mar. Res.*, **1**, 85-94.
- CLARKE, G. L. (1939a), The utilization of solar energy by aquatic organisms. In : *Problems in Lake Biology. Publs. Amer. Assoc. Advance. Sci.*, **10**, 27-38.
- CLARKE, G. L. (1939b), Variation in the transparency of three areas of the Atlantic throughout the year. *Ecology*, **20**, 529-543.
- CLARKE, G. L. (1941), Observations on transparency in the southwestern section of the North Atlantic Ocean. *J. Mar. Res.*, **4**, 221-230.
- CLARKE, G. L. (1954), *Elements of Ecology*. John Wiley and Sons, New York, 534 pp.
- CLARKE, G. L. and BACKUS, R. H. (1956), Measurements of light penetration in relation to vertical migration and records of luminescence of deep sea animals. (In preparation).
- ENGSTROM, R. W. (1947), Multiplier phototube characteristics. *J. Optical Soc., Amer.*, **37** (6), 420-431.
- HAND, I. F. (1937), Review of the U.S. Weather Bureau solar radiation investigations. *Monthly Weather Rev.*, **65**, 415.
- HELLAND-HANSEN, BJØRN (1912), Physical Oceanography. In : *Depths of the Ocean*. (J. MURRAY and JOHAN HJORT), MacMillan & Co., London, 210-306.
- JERLOV, N. G. (1951), Optical studies of ocean waters. *Repts. Swedish Deep-Sea Exped., Phys. Chem.*, **3** (1), 1-59.

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- JERLOV, N. G. and KOCZY, F. (1951), Photographic measurements of daylight in deep water. *Repts. Swedish Deep-Sea Exped., Phys. Chem.*, 3 (2), 63-69.
- KAMPA, E. M. and BODEN, B. P. (1954), Sonic scattering layer studies - an interim report. *Bermuda Biol. Sta. Rept.* (NR165-195). No. 1, 1-28. (Unpublished manuscript).
- KNOTT, S. T. (1953), Design of depth meters for use with cable suspended hydrophones. *Woods Hole Oceanogr. Inst. Ref.* No. 53-44. (Unpublished manuscript).
- MILLER, S. M., MOORE, H. B. and KVAMMEN, K. R. (1953), Plankton of the Florida Current. 1. General conditions. *Bull. Mar. Sci., Gulf and Caribbean*, 2, 465-485.
- OSTER, R. H. and CLARKE, G. L. (1935), The penetration of red, green and violet components of daylight into Atlantic waters. *J. Optical Soc., Amer.*, 25, 84-91.
- SWEET, M. H. (1946), Logarithmic photometer. *Electronics*, 19, 106-109.

A method of recording the direction of travel of ocean swell

N. BARBER and D. DOYLE

Abstract—Wave detectors set in shallow water near a coast can reveal the direction of travel of swell in the deep water providing that the underwater contours of the coast are straight and parallel. Two detectors are sufficient provided that swell of any one periodicity has only one dominant direction of travel.

INTRODUCTION

In a variety of studies it is desirable to know the direction in which swell is travelling. Visual estimates are unreliable since they may be much in error if the swell is being refracted at a shelving coast, and they are in any case restricted to daylight hours. A general method has been indicated previously (BARBER, 1954) involving the synthesis of the power spectrum from the correlation coefficients between a number of wave detectors. It is common, however, for swell to have only one dominant direction of travel, and if two swells are present they usually have different time periods. The correlation method then becomes very simple and the experiments described here use only two wave detectors.

THEORY

When a regular swell is incident on a coast its crest lines may take a form such as that in Fig. 1. Near the coast the waves are refracted by shallow water, or refracted by tidal streams in the manner described by JOHNSTON (1947). If, however, the underwater contours of the coast are straight and parallel, the various crest lines of the swell all have the same shape, and differ only by a displacement parallel to the coast. Thus the separation of the crests measured in a direction parallel to the shore is the same everywhere, in deep water and in shallow water.

We may measure this separation in shallow water by comparing the output signals from two wave detectors that lie at some known interval apart upon a line that is parallel to the shore. If they are a distance D apart and show a phase difference equal to p , the separation of the crests along this line is $2\pi D/p$.

The true wavelength of the swell in deep water is known from the observed period T by the wave equation

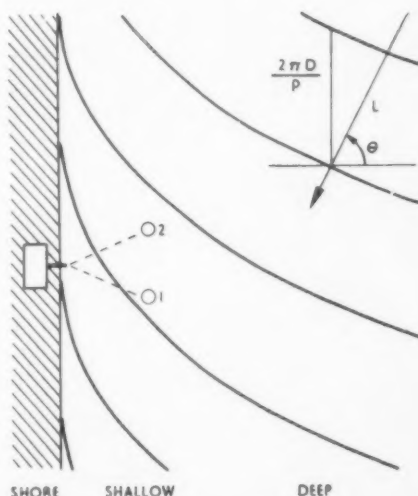


Fig. 1. In the refraction of waves at a straight coast the wave crests have everywhere the same separation in the direction parallel to the coast. It can be measured in shallow water and the wave direction in deep water can be inferred when the true wavelength is known by the observed period.

$$L = gT^2/2\pi.$$

The swell in deep water must therefore be travelling at an angle θ to the normal to the coast, where

$$\sin \theta = Lp/2\pi D.$$

To avoid ambiguity the detectors should not have a separation exceeding $\frac{1}{2}L$, so that it is certain that the phase difference must lie in the range $\pm\pi$.

In simple conditions it will be possible to estimate the phase difference by comparing the two wave signals as recorded by pens on moving paper. This method will be difficult when waves or swell of differing periods, probably travelling in different directions, are present at the same time. Some form of frequency filtering is desirable. Further, it would be advantageous to employ the method of displaying the phase difference which is described in the next section.

A METHOD OF FREQUENCY SELECTION AND DISPLAY

Frequency filtering necessarily produces changes of phase in the signals, but it is essential that we should preserve the true relative phase between the signals from the various wave detectors. Each signal must be filtered in precisely the same way. A complex modulation process meets this requirement (Madella, 1947). In addition it allows the phase difference to be displayed in an Argand diagram. The procedure is shown as a block diagram in Fig. 2.

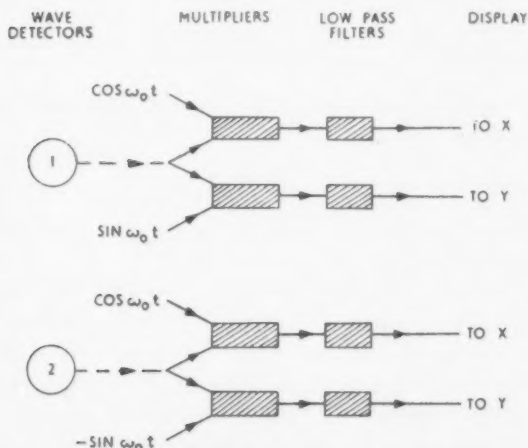


Fig. 2. The electrical signal from each detector is modulated and filtered in two channels. In effect the two wave signals are being multiplied by factors $e^{i\omega_0 t}$ and $e^{-i\omega_0 t}$, respectively, the real and imaginary parts being produced in separate channels.

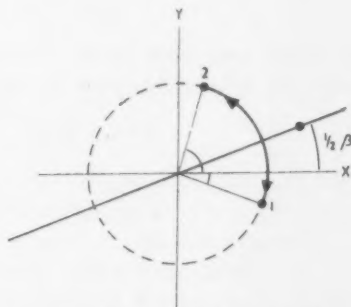


Fig. 3. In the Argand display the two wave signals produce circular motions of the spot in opposite senses, the second signal being always ahead of the first by the phase difference. The combined action of the wave signals is to move the spot along a line inclined at $\frac{1}{2}\beta$ to the X axis.

The effect of this process of analysis is best seen by considering its action on the signals from a simple coherent wave. Each wave detector will give a sinusoidal signal and the two signals will have the phase difference β that we wish to determine. We may write the signals as

$$a \cos(\omega t + \alpha) \quad a \cos(\omega t + \alpha + \beta).$$

When the first signal is multiplied by the factors $\cos w_0 t$ and $\sin w_0 t$ in separate channels we obtain two outputs

$$a \cos (wt + \alpha), \quad \cos w_0 t$$

$$a \cos (wt + \alpha), \quad \sin w_0 t.$$

When passed through the low-pass filters the components of summation frequency are excluded. The difference frequency appears with an attenuation factor $f(w - w_0)$ and a phase change $\psi(w - w_0)$.

The outputs are

$$\begin{aligned} & \frac{1}{2} a f \cos [(w - w_0) t + \alpha + \psi] \\ & - \frac{1}{2} a f \sin [(w - w_0) t + \alpha + \psi]. \end{aligned}$$

If these outputs are made to control the X and Y deflections of some indicator spot moving on a plane, the spot rotates on a circular path in the negative sense as pictured in Fig. 3. This motion may be looked upon as being the complex signal

$$\frac{1}{2} a f \exp -i [(w - w_0) t + \alpha + \psi].$$

The signal from the second wave detector is processed in a similar way but the factors by which it is multiplied are $\cos w_0 t$ and $-\sin w_0 t$. It gives rise to signals which move the indicator spot upon a circular path in the positive sense corresponding to the complex signal

$$\frac{1}{2} a f \exp i [(w - w_0) t + \alpha + \beta + \psi].$$

When both wave detectors are in action these two circular motions combine to give the straight-line motion pictured in Fig. 3,

$$a f \cos [(w - w_0) t + \alpha + \frac{1}{2}\beta + \psi], \quad \exp i \beta/2.$$

The spot moves to and fro on a straight line that is inclined at an angle $\frac{1}{2}\beta$ to the X axis. Thus the phase difference of the signals is displayed directly.

Natural waves or swell are not coherent. We may represent a swell as the sum of an infinite number of coherent waves, (LONGUET-HIGGINS, 1952), which have frequencies that scatter around the mean value w_0 and whose phase differences at the two detectors scatter around some mean value β_0 . The indicator spot then moves randomly over the plane of the Argand display, but it shows a statistically normal distribution with an elliptic form. The major axis of the distribution gives the value of $\frac{1}{2}\beta_0$, this being its angle of inclination to the X axis.

It will be evident that the method requires all the low pass filters to be similar so that they introduce the same attenuation and phase change in all the signals. This is not difficult, however. It is desirable but not essential that the wave detectors shall have equal sensitivity, or else that the gain be adjusted so that the two complex outputs have equal variance. If the gains are unequal the statistical distribution still has its major axis in the correct orientation, $\frac{1}{2}\beta_0$. The only drawback is that the distribution becomes more circular and there is more possible error in determining its major axis. The presence of random errors in the signals of the wave detectors has a similar result.

INSTRUMENTATION

Some experiments have been made at Opotiki in the Bay of Plenty. This locality has a coast with underwater contours that are reasonably uniform, and it is protected from swell arising in the far south where the storms are not subject to direct observation.

The wave detectors were mounted in tetrahedral frameworks 2 ft. 6 in. high, and were laid just outside the surf zone where the mean depth of water was 13 ft. They were connected to shore by lightweight rubber-sheathed electric cable. These detectors were modifications of voltage regulators designed for use in aircraft. In the modified instrument, the water pressure acting on a piston of diameter $1\frac{1}{4}$ inches (sealed from the sea by a rubber diaphragm) was applied to a pile of carbon discs. A voltage from storage batteries on shore was applied to this carbon pile and the current was led through a solenoid in series with the carbon pile. The solenoid acted magnetically on the piston in such a way as to relieve the pressure on the pile. The overall effect of this arrangement is to make the relationship between water pressure and current more linear than it would be with a carbon pile alone.

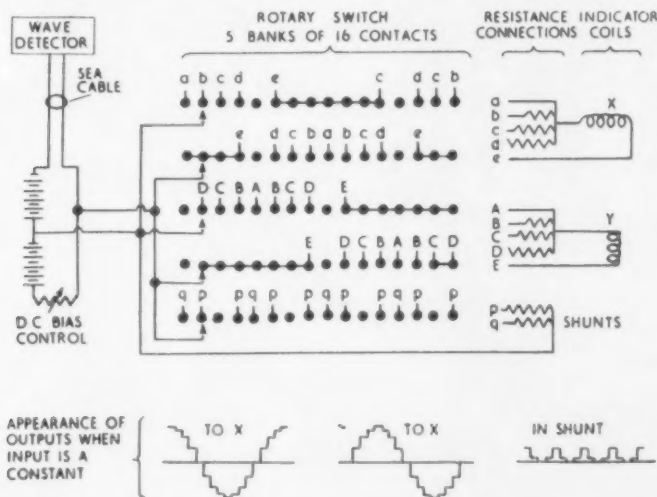


Fig. 4. The fluctuating part $f(t)$ of the current from one wave detector is extracted by a battery bridge. Four banks of the rotary switch are used to extract portions proportional to $f(t) \cos \omega_0 t$ and $f(t) \sin \omega_0 t$. A fifth bank introduces shunts that keep the input impedance constant. With a constant input current the outputs to the X coil, the Y coil, and the shunt have the stepwise form shown below. The second wave detector is connected to a similar circuit and the four outputs operate the four pairs of coils in an indicator.

At the shore station, bridge networks were used to select the fluctuating part of the current from each wave detector. These signals were processed in accordance with the scheme of Fig. 2. The modulation was done by rotary switches, Post Office uniselectors, connected to banks of resistances. The circuit was so arranged that, while a constant impedance was presented to the wave detector, outputs were obtained proportional to the incoming signal multiplied by sine and cosine factors. The action was tested by using constant currents as signals, and it was shown that the two outputs from each signal appeared as currents varying cyclically in sixteen

steps and approximating to sinusoids. The rotary switches were stepped forward by a regular succession of voltage impulses. The number of steps per second could be varied by a potentiometer controlling the time constant of the pulse generating circuit, which was an arrangement of Post Office relays. Thus the rate of cycling of the switch could be adjusted to suit the dominant period of any swell that was being examined. The main features of these circuits are shown in Fig. 4.

The output signals were presented in the form of an Argand diagram by an indicator that could deflect a spot of light in any direction over a viewing screen. Its moving parts were immersed in a clear and very viscous liquid, so that this indicator also acted in place of all four low pass filters shown in Fig. 2. Fig. 5 shows the con-

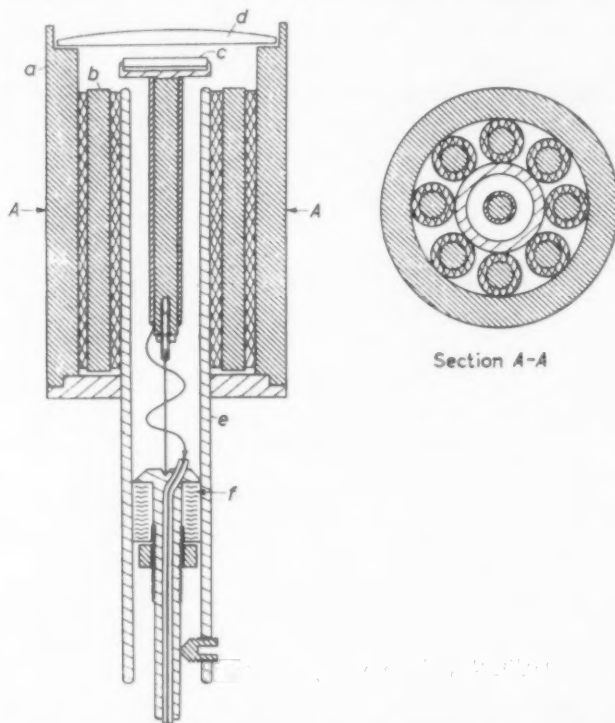


Fig. 5. The indicator. A central vertical magnet carrying a flat mirror (c), is mounted vertically on a wire housed in a brass rod. A rubber plug (f) forms a flexible mount for the rod and allows the magnet to be adjusted by setscrews. The whole is filled with a clear viscous paraffin (kilopoise lubricant 0868, 50% ; medicinal paraffin 50%).

(a) iron sheath. (b) iron cored solenoids. (d) lens. (e) copper tube.

struction of the indicator. In essence it is a flat mirror on top of a magnetized rod which is mounted vertically on the upper end of a short phosphor-bronze wire. This magnet is surrounded by eight iron-cored solenoids acting in pairs. Each pair of solenoids carries one of the four output signals. Subsidiary windings carry alternating current of mains frequency to overcome the magnetic hysteresis of the iron cores. The viscous liquid fills the instrument up to the level of a glass cover which is a lens. This serves to image a light source on the viewing screen after the light has been



Fig. 6. A record obtained in a swell. The circular pattern comes from indicators actuated by only one wave detector. The elliptic pattern is from an indicator actuated by both detectors.

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reflected at the mirror. The indicator is sufficiently sensitive for the signals to actuate it directly, without amplification.

In order to make permanent records the viewing screen is replaced by grade 2 bromide paper. Exposures are made for one hour. It is found best to light the lamp briefly once every half minute, so that each record consists of a cloud of about 120 spots. A sample record is shown in Fig. 6.

RESULTS

The record shown in Fig. 6 was taken when a regular long-crested swell of period between 10 and 11 seconds was arriving at the coast on 17th August at 12.30 hrs. The breakers were between 3 and 5 feet high. The lines of surf suggested that the swell came from an easterly direction, and that the projected wavelength along the shore might be between 600 and 1,200 ft.

The record in Fig. 6 shows two distributions that are roughly circular. These are from indicators that were each attached to only one wave detector. The circular form of these patterns shows that the one-hour sample was statistically adequate. The elongated distribution was given by an indicator that was actuated by both wave detectors. Its major axis is included at -51° to the X axis, indicating that the output of the easterly detector was 102° in phase advance of the other.

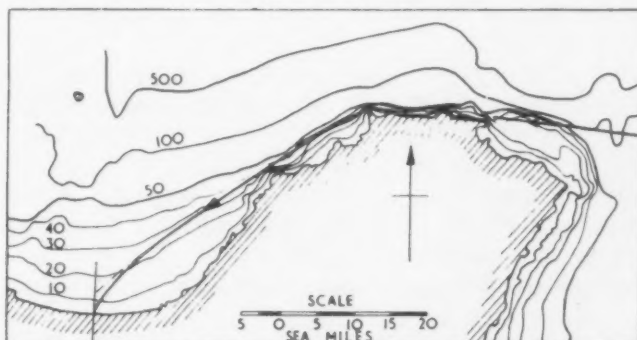


Fig. 7. An estimated ray path for waves of period $10\frac{1}{2}$ seconds arriving at the wave station after passing closely past the Cape.

The instruments had a nominal separation of 180 ft. parallel to the shore. The inference is that the separation of the wave-crests parallel to the shore was 635 ft. In deep water, waves of period $10\frac{1}{2}$ seconds have a wavelength of 565 ft. It would appear that in deep water the swell was travelling in a direction inclined at an angle $\sin^{-1} 565/635$ or 63° to the normal to the coast.

Fig. 7 shows an estimated ray path for waves of period $10\frac{1}{2}$ seconds arriving at the wave station after travelling closely past the Cape. The angle of travel in fairly deep water, 25 fathoms, is only 48° , appreciably less than the estimated value of 63° . This difference may be due to errors in the placing of the wave detectors. The discrepancy could be explained if the eastern detector had in fact been 10 ft. farther to seaward than the other, which is quite possible. The system is evidently rather sensitive to a correct placing of the detectors. Errors of placing are rather less significant if the detectors are in deeper water where the waves have a greater length.

Thus in 32 ft. of water the same error would have arisen if the eastern detector had been 15 ft. to seaward.

It is possible that this swell originated in a storm at a considerable distance to the east of New Zealand, and that it arrived at Opotiki after some refraction past the Cape. The swell at Opotiki was observed during 17 and 18 August. One of us (D.D.) when travelling down the east coast on the morning of the 18th noticed a heavy swell of similar period coming from the easterly sector. Some five days previously, at 18.00 on 12 August (N.Z. time) the S.S. *Haparangi* at a position 36.4°S 104.3°W , which is 1.980 miles to the east of the Cape, reported a swell of period 10

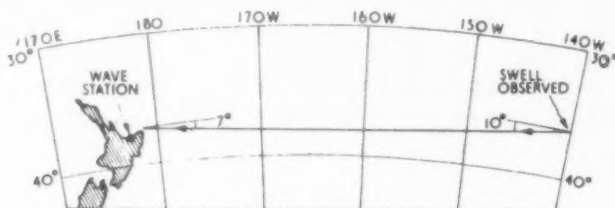


Fig. 8. The expected path of the swell observed by the S.S. *Haparangi* at 36.4°S , 104.3°W . Distance 1.980 m.

seconds height 8 ft. coming from a direction $\text{N } 80^{\circ}\text{E}$. Travelling on a great circle path this swell would arrive directly at the Cape from a bearing $\text{N } 97^{\circ}\text{E}$. (Fig. 8). Assuming group velocities of 15.1 knots and 16.7 knots corresponding to the observed periods of 10 and 11 seconds on arrival, this swell would be expected to arrive at the Cape between 17.00 on 17 August and 05.00 on 18 August. The times and periods agree so well that it seems that this is the swell observed at Opotiki and that it had been refracted by the Cape in spite of its steep coast. The synoptic meteorological charts for the southwestern Pacific showed no other likely source of the swell.

CONCLUSION

The experiments show that the method of analysis and display outlined in Figs. 2 and 3 is practicable and easy to interpret. In the simple form described here it will not resolve two different swells if they have the same or nearly the same time period. Three or more wave detectors would be required as suggested elsewhere.

In the matter of instruments, the carbon pile wave detectors proved unreliable and are not recommended. The indicators are very sensitive to level, and the levelling must bring the central magnet close to the geometrical centre of the solenoids in order for their response to be linear. They worked well, however, after being set up on the concrete floor of the laboratory.

A more complete analysis would be possible if the wave signals were recorded on magnetic tape and rehearsed at high speed. The directions and amplitudes of all the wave components could be found. However, the present apparatus has the advantage that it is simple, and it would be serviceable if one were only interested in the passage of occasional heavy swells. Such observations made at outlying islands

in the South Pacific might be used to give one or two days warning to ships at exposed anchorages elsewhere on the path of the swell.

Department of Scientific and Industrial Research, Wellington, New Zealand.

REFERENCES

- BARBER, N. F. (1954), Finding the direction of travel of sea waves. *Nature*, **174**, 1048.
JOHNSON, J. W. (1947), The refraction of surface waves by currents. *Trans. A.G.U.*, **28**, 867.
LONGUET-HIGGINS, M. S. (1952), The heights of ocean waves, *J. Mar. Res.*, Vol. XI, No. 3, 245.
MADELLA, G. B. (1947), Single phase and polyphase filtering devices using modulation. *Wireless Engineer*, Oct., 310.

The Cariaco Trench, an anaerobic basin in the Caribbean Sea

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Abstract—The Cariaco Trench is a basin in the Caribbean Sea which is anaerobic below depths of about 375 metres to the bottom at 1,400 metres. Below ca. 250 metres the water is essentially isothermal at about 16.9 C. and has practically uniform salinity and density. Hydrogen sulphide reaches maximum concentrations of 0.3 mgA sulphide S per litre, which is about 10% of the concentration found in the depths of the Black Sea. Inorganic phosphate is linearly related to the oxygen and sulphate consumption in a ratio equivalent to 235 atoms of oxygen utilized for the production of 1 atom of phosphate. The anaerobic zone is free of nitrate and nitrite, but some ammonia is present. It is suggested that most of the nitrogen arising from decomposition of organic matter is present as elementary N_2 in solution. The age of the water is estimated to be between 100 and 2,000 years. The physical properties of the trench are compared with those of other isolated basins.

THE Cariaco Trench is a depression about 1,390 metres deep in the continental shelf off the Venezuelan coast. It is separated from the Caribbean Sea to the north and east by a ridge which includes Islas Tortuga, Margarita, Cubagua, Coche, and Farallon Centinela. The sill is nowhere deeper than about 150 metres, thus shutting off the deeper water from that of the Caribbean (see Fig. 1), and enclosing a trench about 100 miles long (east to west) and 40 miles wide (north to south). The structure is superficially similar to the other island arcs with adjacent deep trenches characteristic of the West Indies, but it lies along the axis of the Venezuelan coastal range.

During a cruise of the *Atlantis* in December 1954, Mr. L. V. WORTHINGTON discovered that the trench water was anaerobic from about 500 metres to the bottom, and it was evident from the odour that hydrogen sulphide was present. The area was revisited in February 1955, at which time more extensive chemical observations were made.

CIRCULATION

Above sill depth, the waters of the Cariaco Trench are in free communication with the surface waters of the rest of the Caribbean. Currents of varying strength are reported (Hydrographic Offices, 1949) to enter the region between the islands to the east, and it is clear from salinity and temperature observations that the waters of the trench above sill depth exchange freely with the Caribbean.

Below sill depth, the trench is isolated from the off-lying waters, as shown by comparisons of the vertical distribution of salinity and temperature inside and just outside the sill (Fig. 2).

Within the trench, the temperature decreased rather steadily from surface values of 24° to 26°C to about 18°C just below sill depth. At 460 metres, the temperature had dropped to $17.00^\circ \pm .02^\circ\text{C}$, and from that depth to 1320 metres remained remarkably constant. The lowest *in situ* temperatures, $16.85^\circ \pm .02^\circ\text{C}$, were observed between 554 and 888 metres, while deeper observations were $16.88^\circ \pm .02^\circ\text{C}$. This

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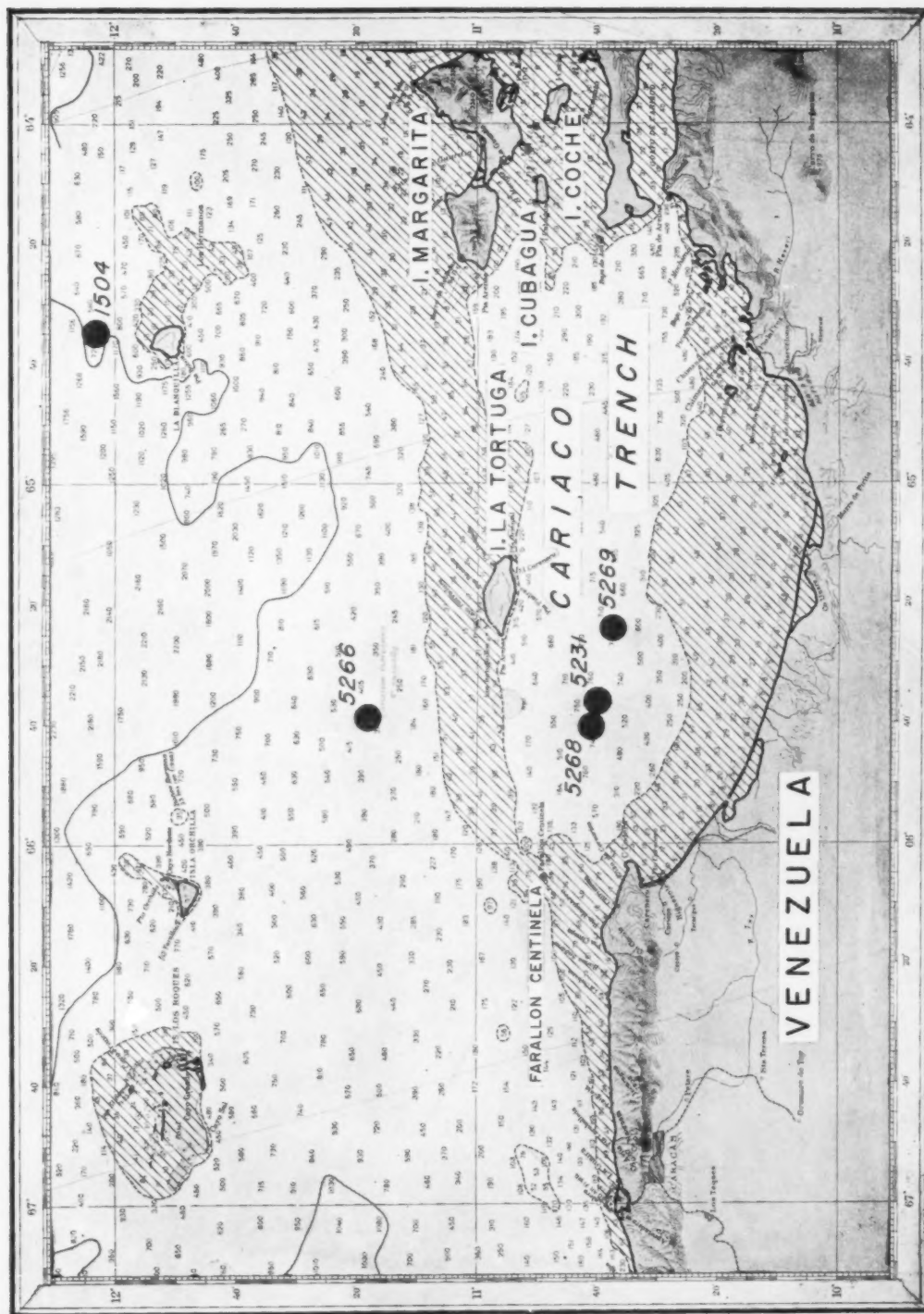


Fig. 1. Location of Cariaco Trench and hydrographic stations, from U.S. Navy H.O. Chart No. 2319, April 1917. 13th Ed., 1950.

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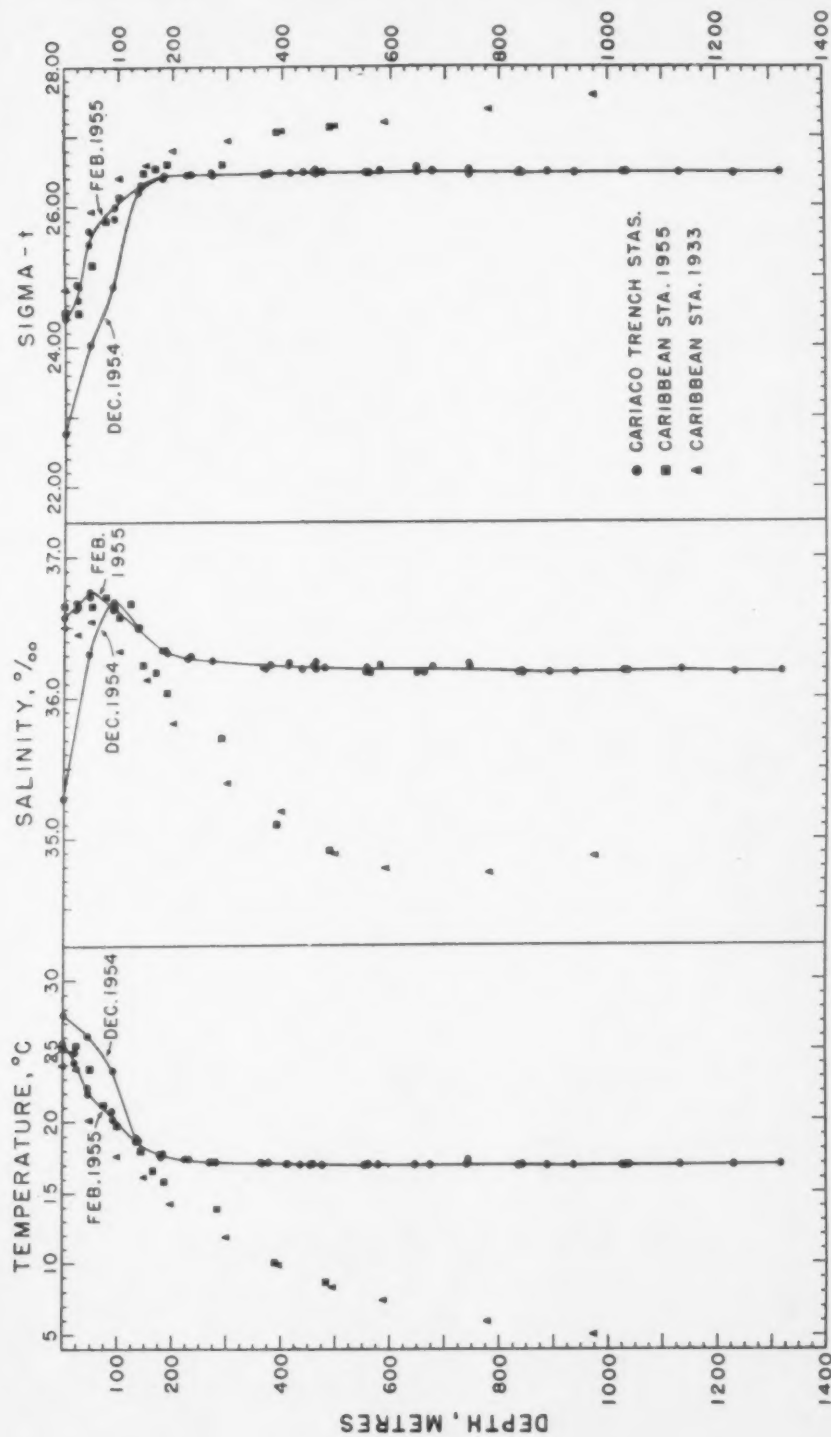


Fig. 2. Vertical distribution of salinity, temperature, and density in the Cariaco Trench and nearby Caribbean. Cariaco Trench stations : 5231, 10° 40' N, 65° 36' W., 5 Dec. 1954 ; 5268 ; 10° 41' N, 65° 40' W., 8 Feb. 1955 ; and 5269, 10° 37' N, 65° 24' W., 9 Feb. 1955. Caribbean stations : 1504, 12° 03' N, 64° 35' W., 15 March 1933 ; 5266, 11° 18' N, 65° 39' W., 8 Feb. 1955.

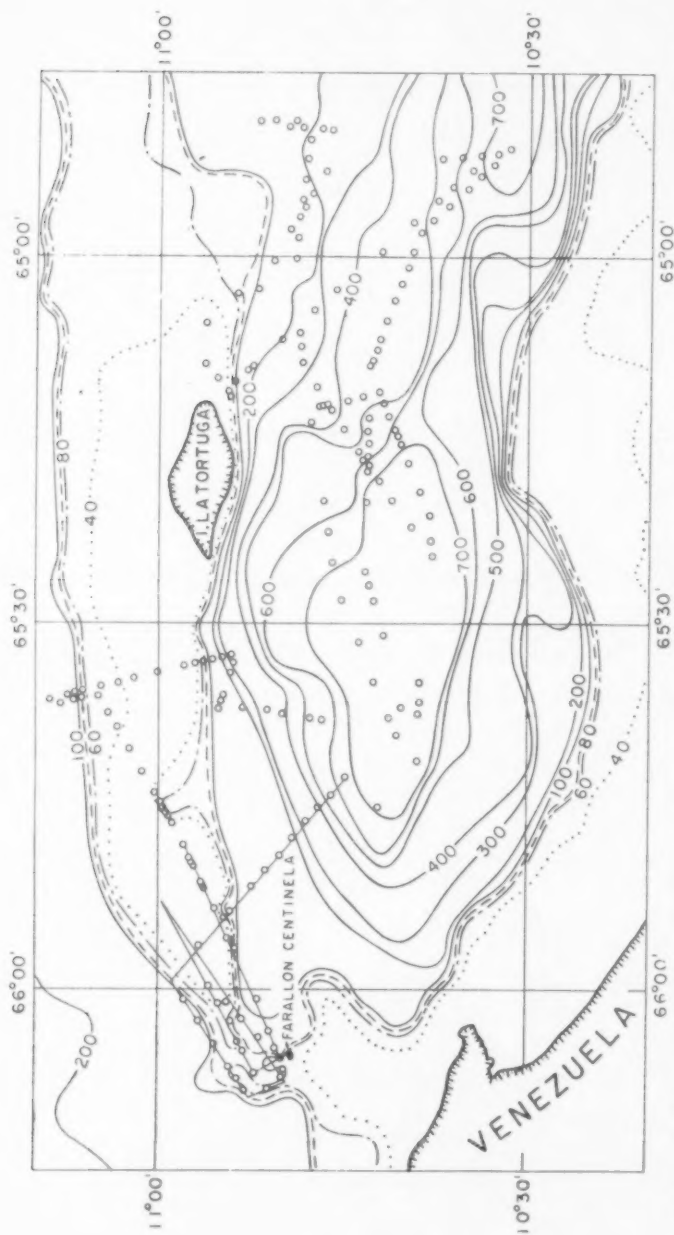


Fig. 3. Bathymetry in the Cariaco Trench, showing the track of the *Caryn* and location of discrete readings from the record of a high-precision echo-sounder.

temperature inversion is apparently the result of adiabatic heating[†]. Just north of the trench, the temperature was similar in distribution to that in the trench to sill depth, but continued to decrease at greater depth, falling to 8.60°C at 488 metres.

The salinity distribution likewise demonstrates the isolation of the water below sill depth. In December 1954 the surface salinity was 35.28‰, and in February 1955 36.57‰, but on both occasions at 180 metres it was 36.33‰. Between 180 and 520 metres the salinity decreased gradually to $36.20 \pm .02$ ‰, and water of this salinity filled the trench below 520 metres. In the Caribbean north of the sill, the salinity continued to decrease steadily with depth to 34.91‰ at 488 metres.

The exchange of Caribbean Sea water with the deep water of the Cariaco Trench depends upon the density structure below sill depth off Farallon Centinela. The depth of the sill is close to 80 fathoms (146 metres) as disclosed by several fathometric traverses by CARYN *et al.* in February 1955 (Fig. 3). The potential density for the deepest water of the trench was $26.51 \pm .02$. North of the sill (station 5266) a density of 26.51 was observed at a depth of 160 metres. At greater depths the density of the Caribbean water exceeded that of water within the trench, indicating that Caribbean water deeper than 160 metres is denied access to the trench. It is possible, however, that small variations in the external density structure may induce intermittent exchanges of such water across the sill.

BIOCHEMICAL PROPERTIES OF THE WATER

The biochemical properties of the water below sill depth also show that it is isolated from the rest of the Caribbean. The oxygen content in the trench water, determined by the Winkler titration, decreased rather regularly with depth to zero at about 475 metres, where hydrogen sulphide was first detected (Fig. 4A). Below this depth, hydrogen sulphide increased with depth to 800 metres below which concentrations of 0.03 mg A sulphide S per litre were found to the bottom[‡].

The total phosphorus concentration determined by HARVEY's (1948) method increased with depth from about 0.1 microgram atoms per litre at the surface to 2.72 µgA per litre at 700 metres. It was impossible to make inorganic phosphate determinations at the time of sampling, and the analyses were made after four to sixteen weeks frozen storage in polyethylene bottles. During this time, the hydrogen sulphide disappeared from the samples and satisfactory determinations, as described by KETCHUM, CORWIN and KEEN (1955), were generally possible. Standards were made up with surface sea water so no salt error correction is necessary. Colour comparisons were made in the photoelectric colorimeter described by FORD (1950). Experience has shown that phosphates determined on frozen samples are somewhat erratic, and some analyses have been discarded because of discrepancies between samples taken at nearly the same depths. These analyses (Fig. 4B) show the same vertical distribution as the total phosphorus. At no depth was the inorganic phos-

[†]Heating by the adiabatic compression of sea water is usually insignificant at depths less than about 2,000 metres. However, the effect is directly proportional to the absolute temperature (PROUDMAN, 1953, pp. 197-201), so that in water having *in situ* temperature of the Cariaco Trench, the potential temperature is about 0.2°C lower than the *in situ* temperature of the deepest part of the trench.

[‡]Throughout this paper, hydrogen sulphide or sulphide is used to indicate the total sulphide sulphur content, *i.e.*, $H_2S + HS^- + S^{2-}$. Sulphides were determined by spectrophotometric determination of the amount of methylene blue formed in the reaction between sulphides, para aminodimethylaniline, chloride and ferric ions. The method was adapted for use in sea water by Mr. SAYED ALI EL WARDANI.

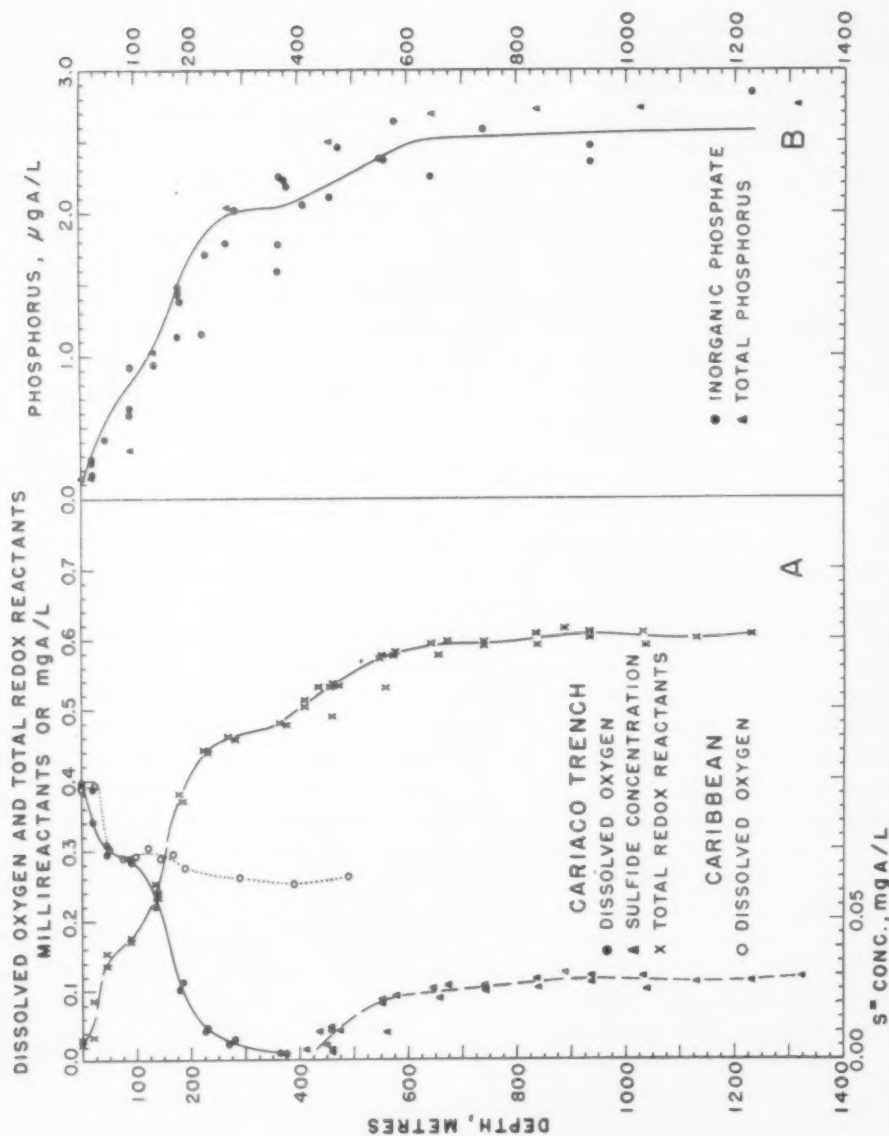


Fig. 4A. Dissolved oxygen in the Cariaco Trench and the nearby Caribbean, sulphide concentrations and total oxygen and sulphate consumed in the Cariaco Trench. The data are from stations 5266, 5268 and 5269. See Figs. 1 and 3 for these locations.

Fig. 4B. Vertical distribution of inorganic and total phosphorus in the Cariaco Trench. The line shows inorganic phosphorus values predicted from the ratio $40U + 4S : P = 235 : 1$ by atoms.

phate content sufficiently different from the total phosphorous to indicate significant amounts of organically bound phosphorous (KETCHUM, CORWIN, KEEN, 1955).

Nitrate, nitrite, and ammonia were determined on samples subjected to the same storage as the phosphate samples. These analyses showed that less than one microgram atom per litre of ammonia nitrogen, determined by the method of RILEY (1953), was present in the surface, but at 50 metres it had decreased to undetectably low concentrations. Ammonia again became detectable at 270 metres, and increased with depth to 8 to 9 microgram atoms per litre at about 550 metres and remained at this concentration through the rest of the anaerobic layer. Nitrate was very low in the surface and increased to a maximum of about $14 \mu\text{gA/L}$ at 180 metres. At greater depths, the concentration of nitrates decreased to traces (within the analytical sensitivity) in the anaerobic layer, essentially disappearing with the disappearance of oxygen and the appearance of hydrogen sulphide. Consistent analyses were obtained with ZWICKER and ROBINSON's (1944) strychnidine method, and with MULLIN and RILEY's (1955) hydrazine method, in which nitrate is reduced to nitrite with hydrazine and the latter determined by diazotization.

Only traces of nitrite, determined by the method of ROBINSON and THOMPSON (1948), were found throughout the water column, and it appears that the major inorganic nitrogen compound present in the anaerobic zone was ammonia.

Titration alkalinity was determined by the method of GRIPENBERG (1937), and the specific alkalinity (titration alkalinity $\times 10^3 \div \text{Cl}\%$, HARVEY, 1955, pp. 160-161) was computed for eleven of the samples from the Cariaco Trench. Ten of these were from depths between the surface and 743 metres, and for all these the specific alkalinity was between 0.122 and 0.131. The value for the other sample, from 1231 metres, was 0.141, indicating a substantial increase in the titration alkalinity in the deep water of the trench. Approximate computations of the contribution of HS^- ions at the sulphide concentrations and pH found in the deep water of the trench indicate that the magnitude of change in alkalinity corresponds to the observed accumulation of bisulphide ions.

The pH , determined with a Beckman model G pH meter, decreased from a value of 8.2 at the surface to 7.8 at 375 metres, and remained approximately uniform at the latter value to the bottom. Some of the determinations in the deep part of the trench indicated that the pH dropped to 7.6, but these are believed to be in error, and were not substantiated by other determinations.

BIOCHEMICAL RELATIONSHIPS IN THE CARIACO TRENCH

In anaerobic waters, the oxidation of organic matter has consumed all the dissolved oxygen, and has led to the reduction of some of the sulphide ions with the production of sulphide. These reactions can be represented by the equations



It can be seen from these equations that one sulphate ion as an oxidant is equivalent to four atoms of oxygen. The amount of oxygen consumed, the apparent oxygen utilization (AOU), is defined as

$$\text{AOU} = \text{O}_2' - \text{O}_2$$

in which O_2 is the observed concentration of oxygen and O_2' the concentration of oxygen dissolved in water having the observed salinity and temperature when in equilibrium with a water-saturated atmosphere (WHIPPLE and WHIPPLE, 1911; REDFIELD, 1948). The amount of sulphate ion consumed is assumed to equal the observed sulphide concentration. Therefore, when AOU and S^- are expressed in milligram (or microgram) atoms per litre, $AOU + 4S^- = \text{Total redox reactants}$.

Table 1. Ratios of carbon, nitrogen, and phosphorus bound in organic matter, and of oxygen consumption to phosphate and inorganic nitrogen compounds formed upon its decomposition, by atoms.

	Derivation	O	C	N	P	Reference
1.	Changes in sea water and analysis of plankton organisms. Phosphate analyses corrected for salt effect according to COOPER, 1938.	—	105	15	1	REDFIELD, 1934
2.	Ratios in line 1, assuming two atoms of oxygen consumed on oxidizing one atom of carbon.	210	105	15	1	
3.	Ratios in line 2, further assuming the oxidation of nitrogen compounds requires four atoms of oxygen for each atom of nitrogen.	270	105	15	1	GILSON, 1937
4.	Average composition of plankton organisms.	—	106	16	1	FLEMING, 1940
5.	Ratios in line 4, and the assumptions in lines 2 and 3 regarding consumption of oxygen and nitrogen.	276	106	16	1	
6.	Analyses of sea water, phosphate analyses corrected as in line 1.	180	—	15	1	REDFIELD, 1934 COOPER, 1938
7.	Cariaco Trench, 50 metres	235	—	15	1	
8.	Cariaco Trench, 50 metres to top of anaerobic layer.	235	—	15-3	1	
9.	Cariaco Trench, anaerobic layer.	235*	—	2-4	1	

*Total redox reactants, $AOU + 4S^-$

Two approximations are inherent in the method described above for calculating total redox reactants. The possible presence of intermediate products from the anaerobic reduction of sulphate is not taken into account, nor is any allowance made for the fraction of the observed hydrogen sulphide which originates directly from the anaerobic decomposition of organic sulphur compounds. The former approximation may result in high total redox reactants while the latter would tend to give low values. Both errors are probably small.

As calculated, the total redox reactants increase with depth to about 680 metres (Fig. 4A), and then remain constant at ca. 0.6 milliequivalents per litre to the bottom.

The ratios between the amounts of phosphorus, nitrogen, and carbon bound in organic matter, and the amount of oxygen consumed when organic matter decomposes with the release of phosphate, nitrate, nitrite, and ammonia, have been reported by

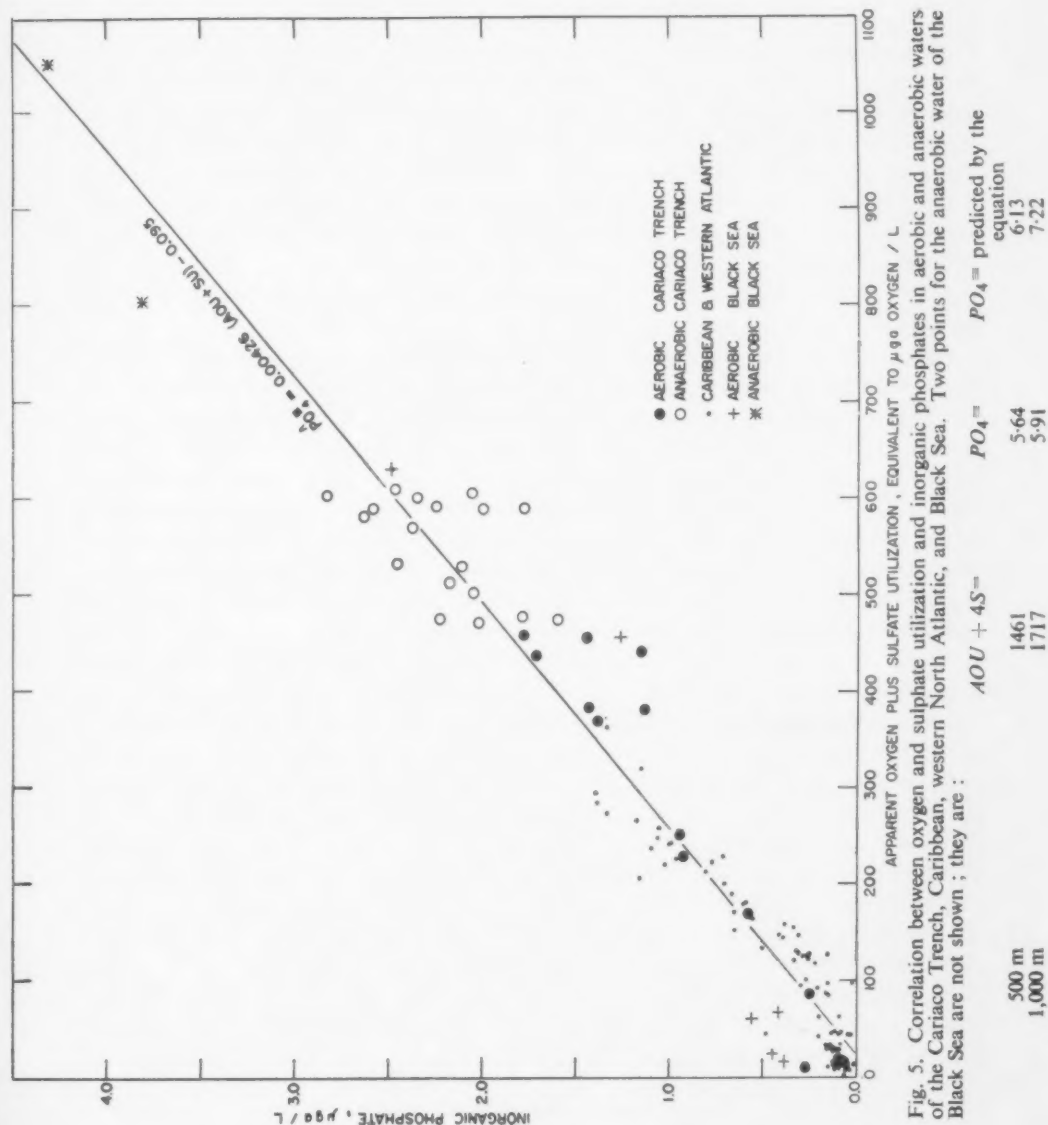


Fig. 5. Correlation between oxygen and sulphate utilization and inorganic phosphates in aerobic and anaerobic waters of the Cariaco Trench, Caribbean, western North Atlantic, and Black Sea. Two points for the anaerobic water of the Black Sea are not shown; they are:

several authors (Table 1). In the Cariaco Trench, the ratio between sulphate reduction and/or oxygen consumption and phosphorus release is shown by the data presented in Fig. 5, in which the line shown is the linear least-squares line of regression of phosphates on the sum of oxygen and sulphate utilized :

$$\hat{PO}_4 = 0.00426 (AOU + 4S^-) - 0.095.$$

The coefficient of correlation is 0.959. The standard error of estimate is $0.21 \mu\text{gA}$ phosphate-phosphorus per litre, showing that the departure of the intercept (0.095) from zero is insignificant. Thus, in the Cariaco Trench, the oxidation to phosphate regeneration ratio is $1/0.00426 = 235$, in good agreement with the other ratios in Table 1, particularly since the nitrogen compounds in the anaerobic part of the Cariaco Trench are clearly not in their highest state of oxidation, and a number somewhere between 212 and 276 : 1 might well be expected. The vertical distribution of inorganic phosphate predicted from the oxygen and sulphate utilized by the 235 : 1 ratio (Fig. 4B) is in good agreement with the observed distribution of phosphate.

Estimates of the oxygen and sulphate utilized and phosphate concentrations in the Black Sea have been made from oxygen and hydrogen sulphide data reported from the *Thor* expedition (SCHMIDT, 1912, p. 65, Station 172), and phosphate data reported by GOLOBOV (1949). In the Black Sea, the anaerobic zone begins at about 150 metres, and the hydrogen sulphide content increases much more rapidly with depth than it does in the Cariaco Trench, until at 1,000 metres it is approximately 10 times more concentrated. However, up to concentrations of $4.30 \mu\text{gA}$ phosphate phosphorus per litre, the same ratio of oxygen plus sulphate reduction to phosphate regeneration is found in both the aerobic and anaerobic layers of the Cariaco Trench and down to 300 metres in the Black Sea. The ratios are shown in Fig. 5 by distinctive symbols. At greater depths in the Black Sea this ratio attains a higher value, and it appears that mechanisms operate other than the oxidation of organic materials with the concurrent release of inorganic phosphate. Among the possible mechanisms are a) the direct assimilation of phosphate by bacteria as observed by RENN (1937) and others and b) the relatively more rapid decomposition of phosphatic organic compounds in the upper layers, permitting only residues low in phosphate to settle to greater depths. SEIWELL and SEIWELL (1938) and COOPER (1935) observed that phosphate was released more rapidly than the nonphosphatic residues when plankton organisms were oxidized. In favour of mechanism a), there are sufficient quantities of organic matter in the deeper layers of the Black Sea, reported by GOLOBOV (1949) as "oxidizability" to satisfy the phosphate deficit predicted by the linear relationship shown in Fig. 5, assuming that the C : P ratio is 235 : 1. In the Cariaco Trench the binding of phosphorous by anaerobic bacteria is not a predominant process, as shown by the absence of significant quantities of organic phosphorous.

NITROGEN REGENERATION

At the nitrate maximum in the aerobic layer of the Cariaco Trench (about 50 metres), the theoretical nitrate to phosphate ratio of 15 : 1 is realized, but at greater depths there is a relative deficiency of inorganic nitrogen compounds. From 50 metres to the top of the anaerobic layer the ratios decrease with depth to about 3 to 4 : 1, with similar ratios prevailing in the anaerobic layer. The maximum concentration of

phosphate in the anaerobic layer is approximately $2.6 \mu\text{gA/l}$. This amount of phosphorus regeneration should be accompanied by $39 \mu\text{gA}$ of nitrogen regeneration. Of this amount, only $8 \mu\text{gA/l}$ can be accounted for, as ammonia. This would leave $31 \mu\text{gA/l}$ of nitrogen to be accounted for. It is probable that the remaining nitrogen released by decomposition is present as molecular, uncombined dissolved N_2 . This view is strengthened by the observations of Kriss (1949) that gaseous nitrogen increases toward the bottom of the Black Sea, and that the deep waters are supersaturated.

At the temperature and salinity of the Cariaco Trench, the equilibrium solubility of nitrogen in sea water is approximately 10 ml/l (RAKESTRAW and EMMEL, 1938a). The amount of nitrogen assumed to be of biological origin, $31 \mu\text{gA}$ or 0.35 ml per litre, is only 3.5% of the amount of atmospheric nitrogen ordinarily present in sea water. Even the careful work of RAKESTRAW and EMMEL (1939b) shows concentrations of nitrogen in sea water which vary from 100% saturation by as much as 7 to 8%, usually by 2 or 3%. Therefore, accumulations of gaseous nitrogen attributable to organic decomposition in the Cariaco Trench are probably too small for detection by a direct analysis of the nitrogen content of the water.

AGE OF THE WATER IN THE CARIACO TRENCH

Three methods can be used to estimate the time that the water has been sequestered in the deep part of the Cariaco Trench, provided the water is not overturning. At present it has not been definitely determined whether such is the case, partly because measurements of the sill depths and of the density structure outside the trench are too incomplete.

A minimum age can be estimated by comparing the quantity of organic matter decomposed below sill depth with the rate of organic production in the photic zone. This calculation involves the assumptions that a) all the organic matter formed in the upper layers rains into the basin and is there oxidized completely, with no deposition of organic detritus on the bottom; b) there is no recycling of nutrients in the layer above the sill; c) the same amount of organic matter enters and leaves the trench over the sill. Since two atoms of oxygen, either molecular or as sulphate, are required to oxidize one of carbon, the amount of carbon consumed below sill depth can be estimated by integrating the consumption of oxygen and sulphate. The carbon consumption thus estimated is $20.55 \times 10^3 \text{ gm C/M}^2$. The rate of organic production in the photic zone has been estimated by Dr. JOHN H. RYTHER to be about $0.48 \text{ gm C/M}^2/\text{day}$, from a carbon-14 determination of the photosynthetic rate. Therefore,

$$\frac{20.55 \times 10^3 \text{ gm C/M}^2}{0.48 \text{ gm C/M}^2 \text{ days}^{-1}} = 40.55 \times 10^3 \text{ days} = 111 \text{ years.}$$

Departures from assumptions a) and b) may be large but they would increase the age estimate, so 100 years is considered to be a minimum. Appreciable amounts of plankton pigments and up to about 4% of organic carbon in sediment cores from the trench prove that there is some departure from assumption a).

A maximum age of the water in the trench can be estimated by assuming that the trench was catastrophically filled with a mass of water having the uniform salinity and temperature now found below 650 metres. If present-day departures from

uniform temperature have been caused solely by molecular conduction, it can be shown that it would take between 1,000 and 2,000 years to raise the temperature of the water column between sill depth and 650 metres to the observed temperatures. A much longer time, between 120,000 and 240,000 years, would be required for the present-day distribution of salt in this region to be accomplished by solely molecular diffusion.

These estimates are based on evaluation of the equation

$$TK_p \left. \frac{\partial P}{\partial Z} \right|_{\text{sill}} = \int_{\text{isothermal layer}}^{\text{sill depth}} [P(Z) - P(i)] dz,$$

in which T is the time in seconds, K_p is the coefficient of molecular diffusion or conductivity for salt or heat, and $\partial P/\partial Z$ is the gradient of salt or heat existing across the sill. $P(Z)$ is the salinity or temperature at depth Z , $P(i)$ the temperature or salinity of the isothermal-isohaline layer. The integration was made graphically. Since it might be argued that the gradient $\partial P/\partial Z$ was zero at the time of catastrophic filling, it has been assumed that it increased linearly with time from zero to present-day values, so that the lesser age represents the time based on the existing gradient, the greater age the time based on $\frac{1}{2}$ of the present day gradient (the assumed average). Values of K_p are $1.4 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-1}$ for heat and $2 \times 10^{-5} \text{ cm}^2 \text{ sec}^{-1}$ for salt (SVERDRUP, JOHNSON and FLEMING, 1942, pp. 61 and 69).

In a third method, the time required to achieve the observed temperature distribution by solar radiation is estimated. Within the limitations of the accuracy of the observations and of the constants for radiation and light penetration, it too should place an upper limit on the age.

The static model described above would require an estimated 160 years of heating by solar radiation alone to achieve the temperatures observed between sill depth and 650 metres. The heat involved is 1.15×10^4 gram calories for the column under one square centimetre. The average total radiation from sun and sky reaching these latitudes is reported by Kimball to be $0.275 \text{ gm cal cm}^{-2} \text{ minute}^{-1}$ (SVERDRUP, JOHNSON and FLEMING, p. 103). If one half of this energy is in the visible light range, and since 0.1% of the visible energy reaches a depth of 150 metres in the Cayman Sea just west of Jamaica (CLARKE, 1937-8), then $0.137 \times 0.001 = 1.37 \times 10^{-4} \text{ gm cal cm}^{-2}$ reaches a depth of 150 metres every minute, is absorbed there or at some greater depth, and converted to heat. Therefore,

$$\frac{1.15 \times 10^4 \text{ gm calories cm}^{-2}}{1.37 \times 10^4 \text{ gm calories cm}^{-2} \text{ min}^{-1}} = 0.84 \times 10^8 \text{ minutes} = 160 \text{ years.}$$

It is obvious that the temperature was not changed by insolation alone, because the salinity changes must also be accounted for. The evidence indicates that both heat and salt have been diffused downward mainly by eddy processes. Any eddy process should achieve the observed result more quickly than molecular processes, so we are inclined towards a shorter rather than a longer age estimate in the range between 100 and 2,000 years. The existing data do not justify more exact estimates.

COMPARISONS WITH OTHER ISOLATED BASINS

The Cariaco Trench differs from other anaerobic marine environments in respect to geomorphology, size, the amount of fresh water influx, the depth of the sill, the stability of the water column, and the degree of exchange of surface waters with the

open ocean. The Norwegian and other fjords, the small semi-enclosed embayments which frequently become anaerobic in the summer, and the Black and Azov seas, all receive large influxes of fresh water which establish extreme density gradients preventing effective vertical mixing. Some of the Norwegian fjords and small embayments may overturn and flush with the advent of winter, but the density structure is essentially due to gradients in the salinity.

Table 2. Comparison of isolated basins.

	Sill depth, metres	Stability ^a of water column near sill		Hydrogen sulphide accumulation, microgram atoms sulphide-sulphur per litre	Age estimate
		Depth, metres	Stability		
Catalina Basin ^b	982	679 831 990 1143	92 31 13	nil	—
Santa Monica Basin ^b	737	579 701 792 884	33 44 22	nil	—
Santa Barbara Basin ^b	475	221 433 524 585	76 88 98	nil	2 to 20 years ^b
Kaoe Bay ^c	40-50	0 25 50 75	1920 520 240	13.4, maximum ^e	—
Cariaco Trench	146 (?)	100 125 150 175	680 440 320	30, at 1,200 M	greater than 100 years
Black Sea ^d	40-50	10 25 50 75	21,000 3,000 3,800	300, at 1,000 M	5,600 years ^f

^a Stability = $\Delta \sigma_t \div \Delta D$ (metres) $\times 10^5$.

^b Data from RITTENBERG, EMERY and ORR (1955).

^c Data from VAN RIEL, HAMAKER and VAN EYCK (1950).

^d Data from station at 43° 05' N. Lat., 38° 50' E. Long., 22 July 1925 (OBERKOMMANDO der KRIEGSMARINE, 1943).

^e From VAN RIEL (1943).

^f From GOLOBOV (1949).

The anaerobic Kaoe Bay in the East Indies (VAN RIEL, 1943) is about 500 metres deep, 18 miles across, and roughly circular. It is essentially land-locked, with limited access of the waters shallower than 45 to 50 metres to the ocean through a sound which is about six miles wide, 28 miles long, and 50 metres deep. Although there are over 80 inches of rainfall a year, the salinity in the bay is about the same as that found at comparable depths in the open Pacific, down to sill depth. It contains

undiluted Pacific ocean water, in which there is no oxygen below 300 to 400 metres, and in which VAN RIEL observed a maximum of 13.4 microgram atoms of sulphide-sulphur per litre at 441 metres.

The Cariaco Trench differs from Kaoe Bay in that it is not land-locked, is much larger, and is considerably deeper. It differs from most small embayments, fjords, and the Black and Azov seas, in that it receives little or no fresh water run-off and is filled with typical, undiluted sea water. The density structures across the sills of Kaoe Bay and the Cariaco Trench result mostly from temperature differences in the water column, rather than to large salinity gradients.

The Cariaco Trench shows some interesting similarities to and contrasts with the basins off the California coast described by EMERY (1954) and RITTENBERG, EMERY and ORR (1955). Each of these basins is a depression in the continental shelf and each contains nearly isothermal and isohaline water from shortly below sill depth to the bottom. However, none of the California basins is anaerobic, and their oxygen content is essentially uniform from sill depth to the bottom. The authors indicate that constant flushing of the basin waters renews the oxygen at a rate which equals or exceeds the rate of oxygen consumption. Such is distinctly not the case in the Cariaco Trench.

One expression of differences in the ease of flushing such basins is the stability of the water column, expressed as the change in σ_t with depth (metres). This property, together with age estimates and sulphide accumulations, is shown in Table 2 for the trenches described by RITTENBERG, *et al.* for the Cariaco Trench, Kaoe Bay, and the Black Sea. The stability at about sill depth increases by one order of magnitude in comparing the California basins with the Cariaco Trench and Kaoe Bay, and by another order of magnitude in comparing the Cariaco Trench with the Black Sea. The age estimates and the amount of sulphide accumulation also change in a similar manner.

SUMMARY

The Cariaco Trench is filled with undiluted sea water, which appears to have been altered principally by the anaerobic reactions of bacteria. The surface waters exchange freely with the rest of the Caribbean, and vertical mixing is impeded more by thermal than by haline stratification. It represents an isolated marine environment in which the biochemical processes of decomposition of organic matter and the concurrent regeneration of its inorganic products have proceeded farther than in any other known place filled with typical oceanic water. It offers, therefore, a location where these phenomena can be observed, relatively isolated and uncomplicated by the sometimes confusing processes of circulation and mixing.

Acknowledgements—The authors wish to acknowledge that the original suggestion to study the Cariaco Trench was made by Dr. A. C. REDFIELD, who became interested in it because its geomorphology suggested to him that it might be a stagnant basin. Mr. SAYED ALI EL WARDANI, of Scripps Institution of Oceanography, made the determinations of sulphides and *pH* during the cruise, and his help is gratefully acknowledged. Suggestions by Dr. REDFIELD, Dr. B. H. KETCHUM, Mr. HENRY

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REFERENCES

- CLARKE, G. L. (1938), Light penetration in the Caribbean Sea and in the Gulf of Mexico. *J. Mar. Res.*, **1** (2), 85-94, (4 figs.).
- COOPER, L. H. N. (1938), Redefinition of the anomaly of the nitrate-phosphate ratio. *J. Mar. Biol. Ass. U.K.*, **23** (1), 179.
- EMERY, K. O. (1954), Source of water in basins off Southern California. *J. Mar. Res.*, **13** (1), 1-21, (6 figs.).
- FLEMING, R. H. (1940), The composition of plankton and units for reporting populations and production. *Proc., Sixth Pacific Sci. Congr.*, **3**, 535-540.
- FORD, W. L. (1950), Seagoing photoelectric colorimeter. *Anal. Chem.*, **22** (11), 1431-1435.
- GILSON, H. C. (1937), The nitrogen cycle. *Sci. Rept., John Murray Exped.*, 1933-34, **2** (8), 21-81.
- GOLOBOV, Y. K. (1949), [Contribution to the problem of determining the age of the present stage of the Black Sea]. (In Russian). *Dokl. Akad. Nauk, S.S.S.R.*, **66**, 451-454.
- GRIPENBERG, S. (1937), On the determination of excess base in sea water. *Comm., Fifth Hydrol. Conf., Helsingfors*, 1936, **10** (B), 15 pp.
- HARVEY, H. W. (1948), The estimation of phosphate and total phosphorus in sea waters. *J. Mar. Biol. Assoc., U.K.*, **27** (2), 337-359.
- HARVEY, H. W. (1955), *The Chemistry and Fertility of Sea Waters*. The University Press, Cambridge, viii + 224 pp.
- KETCHUM, B. H., CORWIN, N., and KEEN, D. J. (1955), The significance of organic phosphorus determinations in ocean waters. *Deep-Sea Res.*, **2** (3), 172-181.
- KRISS, A. E. (1949), [The role of microorganisms in the accumulation of hydrogen sulphide, ammonia and nitrogen in the depths of the Black Sea]. (In Russian). *Priroda*, 1949, (6), 35-46.
- MULLIN, J. B., and RILEY, J. P. (1955), The spectrophotometric determination of nitrate in natural waters, with particular reference to sea water. *Analyt. Chim. Acta*, **12** (5), 464-480.
- OBERKOMMANDO DER KRIEGSMARINE (1943), Schwarzes und Asowsches Meer. Beiheft zum *Handbuch für das Schwarze Meer*, Berlin, 72 pp.
- PROUDMAN, J. (1953), *Dynamical Oceanography*. Methuen & Co., Ltd., London, and John Wiley & Sons, Inc., N.Y., xii + 409 pp.
- RAKESTRAW, N. W., and EMMEL, V. M. (1938a), The solubility of nitrogen and argon in sea water. *Phys. Chem.*, **42** (9), 1211-1215.
- RAKESTRAW, N. W., and EMMEL, V. M. (1938b), The relation of dissolved oxygen to nitrogen in some Atlantic waters. *J. Mar. Res.*, **1** (3), 207-216.
- REDFIELD, A. C. (1934) On the properties of organic derivatives in sea water and their relation to the composition of plankton. In: *James Johnstone Memorial Volume*, University Press, Liverpool, 176-192.
- REDFIELD, A. C. (1948), The exchange of oxygen across the sea surface. *J. Mar. Res.*, **7** (3), 347-361.
- RENN, C. E. (1937), Bacteria and the phosphorus cycle in the sea. *Biol. Bull.*, **72** (2), 190-195.
- RILEY, J. P. (1953), The spectrophotometric determination of ammonia in natural waters with particular reference to sea water. *Analyt. Chim. Acta*, **9** (6), 575-589.
- RITTENBERG, S. C., EMERY, K. O., and ORR, W. L. (1955), Regeneration of nutrients in sediments of marine basins. *Deep-Sea Res.*, **3** (1), 23-45, (6 figs.).
- ROBINSON, R. J., and THOMPSON, T. G. (1948), The determination of nitrites in sea water. *J. Mar. Res.*, **7** (1), 42-48.
- SCHMIDT, J. (1912), Introduction, hydrography, deposits of the sea bottom. *Rept. Danish Oceanogr. Exped., 1908-1910 to the Mediterranean and Adjacent Seas*, **1** (1-3), 269 pp., pls.
- SEIWELL, H. R., and SEIWELL, G. E. (1938), The sinking of decomposing plankton and its relationship to oxygen consumption and phosphorus liberation. *Proc. Amer. Phil. Soc.*, **78** (3), 465-481.

- SVERDRUP, H. U., JOHNSON, M. W., and FLEMING, R. H. (1942), *The Oceans*. Prentice-Hall Co., N.Y., x + 1087 pp.
- U.S. NAVY HYDROGRAPHIC OFFICE (1949), *Sailing directions for the West Indies*, 2. *H. O. Pub.* 129 (6th Ed.) xxiii + 335 pp.
- VAN RIEL, P. M. (1943), Oceanographic results, the bottom waters. Introductory remarks and oxygen content. *Snellius Exped.*, 1929-1930, 2 (5) (Ch. 1), 77 pp.
- VAN RIEL, P. M., HAMAKER, H. C., and VAN EYCK, L. (1950), Oceanographic results, tables, serial and bottom observations, temperature, salinity and density. *Snellius Exped.*, 1929-1930, 2 (6), 44 pp.
- WHIPPLE, G. C., and WHIPPLE, M. C. (1911), Solubility of oxygen in sea water. *J. Amer. Chem. Soc.*, 33 (3), 362-365.
- ZWICKER, B. M. G., and ROBINSON, R. J. (1944), The photometric determination of nitrate in sea water with a strychnidine reagent. *J. Mar. Res.*, 5 (3), 214-232.

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Notes on the bathymetric chart of the N.E. Atlantic

M. N. HILL

(Received 12 March, 1956)

1. INTRODUCTION

DURING geophysical and oceanographic cruises undertaken from Britain during the past ten years it has been possible to obtain a large quantity of sounding information in the area of the N.E. Atlantic neighbouring Britain and France. This information combined with that previously available was sufficient to allow an attempt at detailed contouring of a considerable proportion of the area. The result of this attempt is shown in the accompanying chart, which is presented as much with the intention of indicating what is not known of the area as what is. It is hoped thereby that future sounding lines will be arranged to pass through those areas in which the information is inadequate. It is also hoped that the chart may be of assistance to those working in the area and to those interested in the wide variety of topography which the area provides. The chart overlaps by 3° of latitude the northern area of the bathymetric sketch map published by TOLSTOY (1951); the scale is, however, considerably greater.

On the chart the contours are, wherever possible, spaced at 100-fathom intervals. This interval is small for areas where the basic information is thin or where the slopes are steep; and in the western part of the chart, for example, which includes part of the Mid-Atlantic Ridge, both reasons combine to prevent contouring with this interval being possible. Likewise on the continental slope the gradients are often such that although the basic information is available the 100-fathom contours would be too closely spaced. On the other hand in, for example, the northern part of the area where, in general, the gradients are small, the 100-fathom spacing between the contours is possible.

The contours are dotted where it is considered that their position is uncertain; the degree of uncertainty is undefined, but in general it is only in the neighbourhood of those places where there are continuous sounding lines that it has been thought to be justifiable to draw in the contours undotted. In order that an estimate may be made of the reliability of the soundings the transparent overlay to the chart is divided into 1° squares in which the figures represent the number of spot soundings, most of which will have been obtained by wire. The continuous lines on the overlay show the positions along which continuous echo-sounding profiles have been obtained. These echo-sounding results have all been corrected for the variations of velocity of sound in sea water with depth as provided by MATTHEWS (1939).

In contouring the area, a number of soundings and lines of soundings inconsistent with others in the vicinity were found. Usually those in error were conspicuous and were easily rejected; in some cases however it was not possible to decide which were wrong, and it was necessary to determine the source of the soundings and then to include only those obtained by the more reliable methods or from the more reliable ships.

2. GENERAL TOPOGRAPHIC CHARACTERISTICS OF THE AREA

The area covered by this chart can be divided into distinct topographic regions. Primarily, in the western part there is the rugged topography of the Mid-Atlantic Ridge where the amount of detail prevents any attempt at precise contouring with the present information available. There is one area which has been studied in detail between $46^{\circ}30'N$ and $48^{\circ}N$ and between $26^{\circ}W$ and $27^{\circ}W$; this area, which includes a deep steep-sided valley, will be discussed separately in a future paper. In that part of the Mid-Atlantic Ridge between about $45^{\circ}N$ and $50^{\circ}N$ there are numbers of peaks with minimum depths of between about 700 fathoms and 1,000 fathoms. The smoothed level of the ridge reaches a minimum of approximately 1,300 fathoms at the western edge of the area between $45^{\circ}N$ and $50^{\circ}N$. To the north of $50^{\circ}N$ the axis of the ridge swings to the westward off the area covered by the chart.

The deep-water area of the North East Atlantic basin is bounded to the westward by the Mid-Atlantic Ridge, to the eastward by the continental shelf, and to the north by the smooth and comparatively shallow area which extends from the north of Ireland across Rockall to south of Greenland. The overlay chart shows that in this area there is a good coverage by echo-sounding lines, and a general absence of relief in the topography such as exists in the deeper basin to the south.

In the Bay of Biscay and to the west of the north coast of Spain there are abyssal plains which are well covered by soundings and which perhaps extend north-westwards to a latitude of about $52^{\circ}N$. The known plains show maximum gradients which are less than 1 : 1000. To the north of the Bay of Biscay in the entrance to the English Channel the continental slope is extensively cut by canyon-like features concerning which there is considerable known detail; this detail will be published by Dr. A. A. DAY, who kindly provided the information in this region included on the chart. South-westwards from the south of Ireland the continental slope is indented by the Porcupine Seabight, to the north of which is an area of the slope known as the Porcupine Bank, which shows an abnormally low gradient with no sharp boundary between the shelf and slope.

3. GEOPHYSICAL INVESTIGATIONS WITHIN THE AREA

Gravity observations within the area have been made by MEINESZ (1948) and BROWNE and COOPER (1950). These observations all lie to the east of $20^{\circ}W$. Seismic refraction shooting observations have been obtained at positions scattered throughout the area, and the results of some of these have been published by HILL (1952) and HILL and LAUGHTON (1954). More recent results from fifteen additional stations will be published by T. F. GASKELL, M. N. HILL and J. C. SWALLOW in the near future. Heat-flow measurements through the floor of the ocean have been made by BULLARD (1954) at six positions within the area bounded by $48^{\circ}N$ and $50^{\circ}N$ and $12^{\circ}W$ and $19^{\circ}W$.

4. ACKNOWLEDGEMENTS

We are much indebted to the Hydrographer of the Royal Navy for placing at our disposal the basic information from which this chart has been drawn. A large proportion of the echo-sounding lines have been obtained in cruises of H.M.S. *Challenger* and R.R.S. *Discovery II*. We are grateful for the assistance of Dr. J. C. SWALLOW who has been present on many of the cruises of both these ships, and also

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to Dr. H. F. P. HERDMAN who has been responsible for much of the information obtained from the *Discovery*.

The labour of drawing the chart has, to a great extent, been undertaken by Mr. J. BLAGDEN of Trinity College, Cambridge. We are grateful to him for the painstaking care with which he undertook this work. Part of the heavy cost of the production of the chart has been met by a grant from UNESCO; without this financial assistance it would not have been possible to print the chart in colour.

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REFERENCES

- BULLARD, E. C. (1954), The flow of heat through the floor of the Atlantic Ocean, *Proc. Roy. Soc. A* **222**, 408-429.
HILL, M. N. (1952), Seismic refraction shooting in an area of the Eastern Atlantic, *Phil. Trans. A* **244**, 561-596.
HILL, M. N. and LAUGHTON, A. S. (1954), Seismic observations in the Eastern Atlantic, *Proc. Roy. Soc. A* **222**, 348-356.
MATTHEWS, D. J. (1939), Tables of the velocity of sound in pure water and sea water, *Hydrographic Department, London, Publ. No. HD 282*.
MEINESZ, F. A. V. (1948), *Gravity Expeditions at Sea (1923-1938)* Vol. IV, Waltman (A. J. MULDER), Delft.
TOLSTOY, I. (1951), Submarine topography in the North Atlantic, *Bull. Geol. Soc. Amer.* **62**, 441-450.

Note—Additional copies of the chart can be obtained from the publishers of *Deep-Sea Research*. For details, see the back cover of this issue.

IN MEMORIAM

Haakon Hasberg Gran

1870-1955

A PIONEER in the exploration of the oceans, Professor H. H. GRAN, quietly passed away on 2 June 1955, at the age of eighty-five years. Although his scientific activities ended nearly twenty years ago, his publications nevertheless are still an important source of information and stimulation to students of marine phytoplankton. Indeed, they provide an introduction to phytoplankton studies to-day and are a testimonial of his achievement in developing our modern concept of the productivity of the oceans.

GRAN worked in various aspects of marine research: the taxonomy, ecology, and physiology of phytoplankton, the morphology of zooplankton, marine bacteriology, hydrography, and the taxonomy and ecology of benthic algae. In all these studies he made essential contributions which have been the basis for further work. GRAN's broad approach to the problems of the sea was closely tied up with the practical facilities offered within his scientific environment.

A keen eye, an able hand, and a clear mind made him a first-rate taxonomist. His early training while studying under the prominent algologist, Professor N. WILLE, provided him with a sound background for his later work when he turned to the free-floating vegetation of the sea. Although taxonomists from EHRENBURG to CLEVE had described a great number of marine phytoplankton species, GRAN added a long list of new species of important diatoms and dinoflagellates. In *Nordisches Plankton*, Vol. 19, he compiled a flora of the plankton diatoms of Northern Seas which long remained a most useful tool for students of marine plankton.

After his university years GRAN was a research assistant in the Norwegian Fisheries Research Department. His friend JOHAN HJORT was just re-organizing the work, and GRAN became a member of the team working with HJORT, NANSEN, NORDGAARD, and other younger members of the staff. This team proved to be most stimulating to marine research in Norway. During this period GRAN took part in numerous cruises in the Norwegian Sea, in the Skagerak, and in Norwegian coastal waters, which gave him a first-hand knowledge of the sea. The combined hydrographical-biological surveys, which were undertaken then, disclosed the important features of the close interrelationship between the marine environment and the plankton population. The annual cycle of the phytoplankton in the various areas of the coastal region of northern Europe was described. GRAN was also able to disprove CLEVE's theory of the predominant importance of long-distance current-transport for the occurrence of Arctic forms in a boreal area, and to show that changes in the qualitative composition of the population resulted from seasonal changes in the environment. His comprehensive study *Das Plankton des Norwegischen Nordmeeres* (1902) is a synthesis of the results obtained through a combination of taxonomic, autecological, and synecological approaches towards understanding the complicated pattern of quantitative and qualitative changes in the phytoplankton populations of northern waters. Through his participation in the North Atlantic Deep-Sea Expedition with the *Michael Sars* in 1910 GRAN became acquainted with the biology of the high seas. His report on the phytoplankton in MURRAY and HJORT's *The Depths of the Ocean* served for a long time as the best introduction to this aspect of marine ecology.

From the time of its foundation GRAN was an active member of the International Council for the Exploration of the Sea and for many years served as Chairman of its Plankton Committee. In 1912 the council organized an international survey of the North Sea and the southern part of the Norwegian Sea, and GRAN worked up the phytoplankton material, assisted by Miss C. LEEGAARD and Miss H. OGILVIE.

GRAN studied material from the most varied geographical regions: from the Arctic and the Antarctic, from the Pacific and from various parts of the Atlantic; but the Norwegian coastal

waters, where he started his field work, always remained the centre of his interest. In a number of papers he described the most spectacular feature in the annual cycle of phytoplankton: the vernal outburst after the winter minimum. He discussed the ecological background for its occurrence and the different development of the population at this time of the year within the fjords, on the continental shelf, and at its outskirts. He stressed the importance of initial populations which could take advantage of the improved light conditions in early spring. At the time, information on the nutrient content of the water was too scarce to obtain a more complete picture of the factors involved.

His last survey was carried out in the Gulf of Maine and the Fundy region, the International Passamaquoddy Fisheries Commission having invited him to be in charge of the phytoplankton section of its survey programme. This study gave GRAN the great satisfaction of seeing some of the secrets unveiled which had long puzzled him, notably the difference in the time of the spring diatom outburst and the variation in the summer-autumn vegetation from one Boreal area to another. Local differences in the stability conditions and the turbidity of the waters were found to be decisive factors. He was fully aware that marine phytoplankton still offered a variety of problems, but he felt that he had achieved what he might expect to accomplish with the methods which he had developed.

From 1905 until he retired in 1940 GRAN held the chair of general botany at the University of Oslo. His main field of teaching was plant physiology, which for a short period he had studied with Professor H. PFEFFER in Leipzig, and through his university work he obtained a knowledge of plant physiology which formed a most useful background for his plankton studies.

In 1907 he made his first experiments to determine the rate of multiplication in diatoms and dinoflagellates, and he also studied the effect of additions of various nitrogen compounds upon growth. In collaboration with Professor TORBJØRN GAARDER he developed a method for estimating the actual production of organic matter by phytoplankton. This method is still in use, although it is now partially replaced by STEEMANN NIELSEN's tracer method. He also tried to ascertain experimentally whether the phytoplankton excretes organic compounds into the water, a problem which recently has been brought into the foreground through the discussion of ectocrine substances in general.

In marine bacteriology GRAN's name is associated with the bacteria decomposing agar-agar, which he was the first to describe. He also studied denitrifying and nitrate-reducing bacteria from the sea.

GRAN's position as one of the prominent oceanographers of his time is not due only to the impressive contributions reported in his publications, but also to the stimulating influence of his clear-minded and active personality. His imagination and his great fund of knowledge made it possible for him to see the essential problems and transmit his enthusiasm for them to colleagues and students who were unfamiliar with his speciality. It was obvious that the restricted facilities offered in a small country prevented him from starting work in new fields which he could see had to be tackled to solve the problems he encountered, but of this he never complained. His disposition was positive and friendly and he was, therefore, a most stimulating teacher and colleague who will be remembered with gratitude by his friends all over the world.

T. BRAARUD

LETTER TO THE EDITORS

The temperature increase in Caribbean deep water since 1933

In a recent paper in this journal (WORTHINGTON, 1955) I presented a chronology, based on oxygen consumption, in which a date (1790) was assigned to the isolation of the deep water in the Caribbean Basin from that in the Cayman Basin. For this chronology the observed rate of oxygen loss in the Caribbean deep water over the last twenty years was presumed to have been the same since the time when this water was saturated with oxygen. As we knew the amount of oxygen that this water can contain, it was a simple calculation to arrive at a date for its formation.

The admitted weakness in this dating system was that, if the water were much below its saturation point when it flowed over the sill, the filling of the basin would have to be moved into the more recent past. At the time this paper was submitted no great attention was paid to the increase in temperature (WORTHINGTON, 1955) which accompanied this oxygen loss, other than that its existence was attributed to eddy diffusion from higher levels. A more recent study of this temperature increase has provided some evidence that the Caribbean Basin was indeed cut off at a more recent date than the one assigned in the chronology.

The oceanographic section which provided the new temperature and oxygen data closely followed a section made in 1933. In the following table are listed the average potential temperatures at various levels in both sections. Figures in parentheses are the number of stations which were used.

Depth, M	Potential Temperature °C		
	March, 1933	December, 1954	Gain
1500	4.028 (9)	4.075 (6)	0.047
1600	3.973 (9)	4.009 (6)	0.036
1750	3.928 (9)	3.952 (6)	0.024
2000	3.886 (9)	3.901 (6)	0.015
2500	3.842 (5)	3.850 (5)	0.008
3000	3.832 (5)	3.837 (5)	0.005

In spite of the small number of observations at each level the curve of temperature gain versus depth is surprisingly smooth.

The minimum potential temperature found on both sections was 3.80°. This occurred at the greatest depth sampled on each section (4960 m in 1933, 5445 m in 1954). No change in temperature can be detected at these depths. It is not unreasonable to assume that at the time the deep waters of the Caribbean were cut off from the outside they had a potential temperature of 3.80° from the sill depth down to the bottom - in other words that they were neutrally stable - and that the increasingly stable conditions which are found nowadays are due to the supply of heat from above.

If the measured rate of temperature increase at each level has remained the same since the basin waters were cut off, it is possible to arrive at a date for that occurrence. For instance, at the 1500 m level the temperature in 1954 was 4.075°, or 0.275° more than 3.80°, the assumed temperature at the cut-off date. The rate of gain in temperature was 0.047° in 21½ years, so

$$T = 21.75 \times \frac{0.275}{0.047} = 127 \text{ years before 1954.}$$

If the same calculation is carried out for the other levels we get the following answers :

1500 m	1827
1600 m	1828
1750 m	1816
2000 m	1808
2500 m	1818
3000 m	1793

The value at 3000 m seems out of line, but an increase of 0.001° at this level would change the answer to 1816. The others hold pretty close to the average, around 1819. This method can probably be refined, but there seems little use in doing so until there are more modern observations. According to this average the water which filled the deep Caribbean Basin was about 30 years old when it passed over the sill, if we accept the formation date set by oxygen consumption.

No great accuracy can be claimed for either method of dating but the important thing seems to be that both methods agree in order of magnitude. The question of whether this water is 150 or 1,500 years old is the fundamental one at present, and the new evidence favours the more youthful ocean, on the basis of both temperature gain and oxygen loss.

L. V. WORTHINGTON

Contribution No. 666 from the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

REFERENCE

WORTHINGTON, L. V. (1955), A new theory of Caribbean bottom-water formation. *Deep-Sea Res.*, 3, 82-87.

NEWS AND NOTES

UNESCO'S objectives in establishing the International Advisory Committee on Marine Sciences

THE approval last November by the UNESCO Executive Board of the statutes of the International Advisory Committee on Marine Sciences has cleared the way for UNESCO to offer its services to the world's scientists in all fields who apply their studies to the solution of problems related to the oceans.

UNESCO could not have chosen a more appropriate domain to which to extend its activities since, as pointed out by the interim committee meeting held in Tokyo last October, "the oceans are international and hence the marine sciences are a natural field for international collaboration. No one country can find out all it needs to know about the sea . . ."

According to the statutes, the committee is established to advise the Director General concerning the promotion of international collaboration in the marine sciences and concerning the preparation and execution of marine science research projects within the programme of UNESCO, taking into account related programmes of the United Nations and other specialized agencies, in order:

- (a) to increase fundamental scientific knowledge as such;
- (b) to gather and co-ordinate scientific information intended for application in improving the living conditions of mankind.

The primary function of the advisory committee is then to suggest plans for the activities of the marine sciences programme sponsored by UNESCO. The yearly budget appropriated directly to the programme may not be large, but other UNESCO activities such as its fellowships, technical assistance and "Aid to Member States" programmes may eventually be mobilized to the benefit of marine sciences, according to recommendations that may issue from the committee.

On other occasions the mediation of UNESCO might alone suffice to bring about a desirable effect through its influence and prestige. The presence of representatives of the United Nations and its interested specialized agencies as well as those of the International Council of Scientific Unions, its interested adhering unions, and of various other organizations connected with marine research at sessions of the UNESCO Marine Sciences Committee, assures good contacts with these organizations and the activities they represent.

The first instance of UNESCO's interest in aiding marine research might be traced to a meeting of three people in Djakarta in 1951. In April of that year, Dr. ALEXANDER WOLSKY representing

the UNESCO Science Co-operation Office for South East Asia discussed with Dr. G. L. KESTEVEN, then General Secretary of the Indo-Pacific Fisheries Council, and Dr. J. D. F. HARDENBERG, also from IPFC, the proposal for establishing an international oceanographic institute for the Indo-Pacific region. Developments from the ideas conceived at this meeting resulted in a "Resolution on International Oceanographic Requirements" transmitted to UNESCO by FAO after its adoption by the IPFC in October 1952.

No brick-and-mortar establishment materialized out of this IPFC recommendation: the matter was considered by a group of sixteen experts convened in Manila by UNESCO in November 1953; the consensus of this meeting was favourable to the establishment of an institute; but later developments brought the difficulties more and more to the foreground, so that the mode of approach to the problem of helping marine research was altered. A policy of trying "to achieve a gradual development by concentrating first on the co-ordination of national research programmes and on the training of specialized personnel" was recommended by the International Advisory Committee on Research in the Natural Sciences Programme of UNESCO at its first session in April 1954.

At the 8th Session of the UNESCO General Conference, held in November of the same year in Montevideo, the marine sciences programme was conceived for the first time in its present form. A first step was to call a meeting of experts to discuss the terms of reference and mode of operation of the proposed International Advisory Committee on Marine Sciences, and this meeting took place in Rome in May 1955.

Pending the approval of the statutes by the Executive Board, nine interim committee members gathered in Tokyo in October 1955 together with the representatives of interested international organizations. Their recommendations ranged from a general consideration on the oceanic areas of which more information was urgently required, to specific matters such as the extension of the Equapac Project to Australian waters.

Recent activities have included symposia (physical oceanography, Tokyo, October 1955; plankton, São Paulo, November 1955), training courses (methodology of marine biological research, São Paulo, October-November 1955), fellowships (eight to cover the period 1955-56).

A forthcoming meeting of the Marine Sciences Committee will be held in October 1956 on the west coast of South America. Procedures are in progress for appointing the nine members to constitute the international committee.

It is understood that a Special Committee for Oceanic Research is being proposed by ICSU to maintain a continuing programme for marine studies initiated during the International Geophysical Year 1957-58. Since this ICSU Committee and the UNESCO Marine Sciences Committee may have some of their members in common, it should guard against duplication of effort. It goes without saying, however, that a harmonious division of responsibilities between the two committees will go far in advancing scientific knowledge and its application to the welfare of mankind in the as yet little-known oceans of the world.

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ERRATUM

SURVEY of a sea peak in the Mozambique Channel, Vol. 3, No. 2, pp. 145-149 :

p. 145, line 23 : 40° 30' East
should read 41° 30' East.

p. 148 : Fig. 3 is incorrectly stated to be on a scale 7,200 feet to 1 inch.
When reduced for publication purposes, this scale ceased to apply.

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Echo-sounder observations of midwater nets and their towing cables

RICHARD H. BACKUS and J. B. HERSEY

(Received 21 March, 1956)

Abstract—By echo-sounding from a following ship it has been possible to determine the shape of towing cables as well as the depth to a net with varying amounts of wire out. It was found that at 2.5 knots the depth to the Isaacs-Kidd midwater trawl can be closely approximated by computing it from the wire angle measured at the surface.

INTRODUCTION

ECHO-sounders have been put to many uses since their development for measuring water depth. A recent application was that of WOOD and PARRISH (1951) who observed ground and midwater trawls in action. They examined the dimensions of the mouths of nets being towed and the contact of ground trawls with the bottom.

A programme of fishing with two-metre stramin closing nets and the ten-foot Isaacs-Kidd midwater trawl (IKMT) was carried out by our institution during the summer of 1953. In the absence of a reliable depth meter it was suggested that the echo sounder be used to determine the relationship between length-of-wire and depth-of-net. At the same time a telemetering depth meter was being developed for use with nets (Dow, 1954) and it was proposed that echo soundings provide one of the checks on the performance of this meter. On the echo-sounder record of an exploratory run, portions of the towing cable were clearly detectable as well as the net itself. It was then decided that with suitable range information, the shape of the towing cable could be determined.

PROCEDURE

The IKMT is described by the Scripps Institution of Oceanography (1953). The two-metre net used is described by LEAVITT (1935 and 1938). These nets were towed by the research vessel *Blue Dolphin* on $\frac{3}{8}$ " 7 by 7, galvanized aircraft cord at approximately 2.5 knots. The length of the towing cable was measured by a standard type meter wheel (similar to the G. M. Mfg. Co.'s #400) made for $\frac{5}{32}$ " wire. A correction of 6% has been added to indications of wire out to allow for the use of $\frac{3}{8}$ " wire on this meter. The research vessel *Bear* made the echo-sounder observations with an Edo Corp. AN/UQN-1B 12-kc echo sounder.

Since the fishing gear did not tow directly astern of *Blue Dolphin* but slightly off the starboard quarter it was necessary to conn *Bear* by sighting along the towing cable and relaying instructions by radio telephone. Range between *Bear* and *Blue Dolphin* was determined by stadimeter. On *Bear's* first echo-sounder contact with the fishing gear, range observations were begun. A series of "marks" from the stadimeter operator on *Blue Dolphin* were relayed to the echo-sounder operator on *Bear* by radio telephone. These marks were entered on the echo-sounder record and the corresponding ranges were logged on *Blue Dolphin*.

On 23 August, a total of seven echo-sounding runs was made. In these runs the IKMT depressor (without net) was fastened to the end of the towing cable. The telemetering depth meter was placed about five metres above the depressor and the two-metre stramin net was fastened to the wire about 5 metres above the depth meter. This gear was first set with 636 metres of wire out and Runs 1-3 were made. The gear was then retrieved and it was discovered that the net had not opened. The gear was then set as before save that 535 m of wire were paid out. Echo-sounding Runs 4-7 were then made. When the gear was retrieved it was found that the net had again failed to open and also that the frame that supported the depth meter was badly bent. This indicated that at some time during the haul the various parts of the gear did not tow in their proper relationship.

On August 24 a total of 21 echo-sounding runs was made on the IKMT (complete) alone. These runs were made with varying lengths of towing cable as follows: 320 metres - 2 runs, 530 - 2, 742 - 2, 903 - 1, 1007 - 8, 1113 - 2 and 1221 - 4.

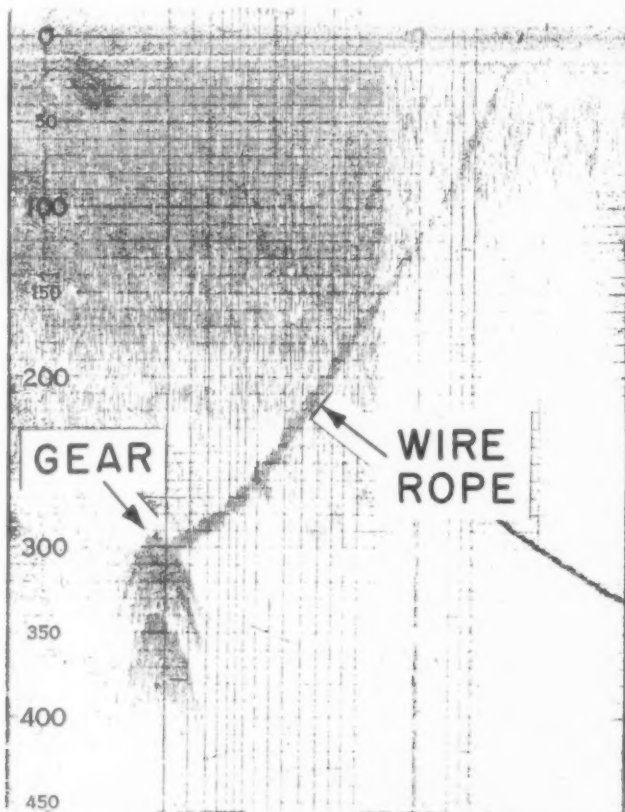


Fig. 1. Edo echo-sounder record of Run # 6, Aug. 23, 1953 on two-metre stramin, telemetering depth meter and 10-foot IKMT depressor.

ANALYSIS OF RECORDS

The following method has been used to interpret the echo-sounder records (Fig. 1) which resulted from these runs:

1. A time scale in arbitrary units was laid off on the echo-sounder record. The number of time units from some zero point (usually the trace of the net or "Mark" 1) to the successive range marks was plotted on graph paper against the corresponding range as determined by stadimeter. This relationship should be linear on the assumptions that *Bear's* rate of closure with *Blue Dolphin* was constant and that the rate of paper advance of the echo sounder was constant. A straight line was fitted to these points and this graph was used to determine corrected ranges at any point on the record during an echo-sounder run.

2. At a number of points where the echo-sounder record could be clearly read the indicated depth to the cable or net was recorded. Zero correction, sound-velocity correction and transducer-depth correction were added in that order. Because the towing cable was in a sloping plane "up" which the *Bear* echo sounded, the depth values at a given range are too small because the shortest effective path between the transducer and the wire is not normal to the sea surface but normal to the wire. The amount of this correction is determined by the slope of the wire; the greater the slope, the greater the correction. For this purpose the echogram of the cable was divided into a few straight segments and the slope of these approximations calculated from the change in indicated depth and the change in corrected range. Once these slopes were known the suitable depth-correction factor was computed. This correction varies from about $\frac{1}{2}$ of 1% to about 6%.

An error for which one cannot correct is that which enters from the *Bear's* echo sounder not being directly over the towing cable or net. Assuming an effective sound transmission and reception cone of 30° at the apex, the maximum error resulting from transmission along an hypotenuse would amount to about 4%. We have attempted to minimize the results of this error by showing some of the variation encountered in the more successful runs (in which the error would likely be small).

Furthermore, we have previously noted errors in traveltime measurement by the Edo echo sounder as high as 6%. This error is due to friction in the belt drive of the recording styli and therefore the error is a negative one (depth indications too low). In the present case this error, if existent, was unknown and we have assumed it to be zero.

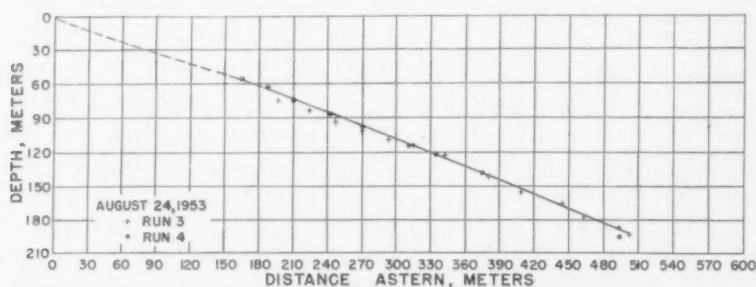


Fig. 2. Shape of the cable towing a 10-foot Isaacs-Kidd midwater trawl with 530 m of wire out. Speed about 2.5 knots.

RESULTS

Fig. 2 shows the shape of the lower two-thirds of the cable when the complete IKMT was being towed alone (Runs 3 and 4, 24 August). The values obtained for both runs are plotted but the minimum soundings are used to draw the line represent-

ing the cable. The part of the cable for which we have soundings is slightly concave downward. If the entire cable were of this shape the net should reach a greater depth than that computed from the wire angle measured at the surface. We find that the depth to the net, as determined by echo sounder, is always slightly less than that computed from the wire angle. Therefore we conclude that the upper one-third of the cable (for which we have no soundings) must be slightly concave upward and we have shown it as such in the figure. However, we might assume a negative error of 10% in depth measurement due to friction in the stylus belt of the echo sounder, and increase all soundings on the cable by this amount. Then, assuming the cable to be flat in the upper portion, the wire angle at the surface would necessarily be about 69° . Since this is within the limits of our observation ($67^\circ \pm 2$) a flat shape in the upper portion is a possibility.

We estimate from the data in SIO (1953) that the tension on the towing cable during these runs was about 1500 pounds.

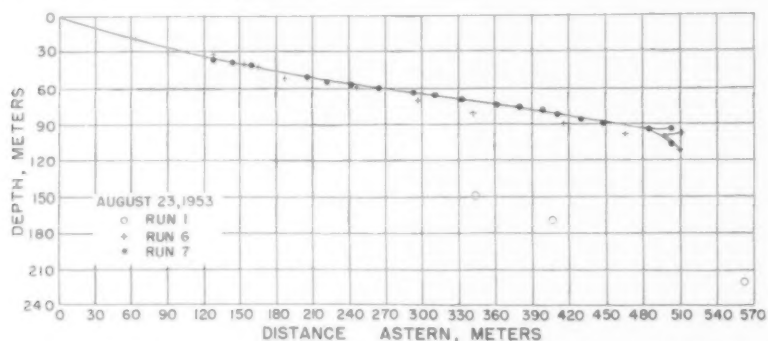


Fig. 3. Shape of the cable towing a closed two-metre stramin net, telemetering depth meter and 10-foot IKMT depressor. Gear is presumed to have been fouled during Runs 6 and 7 and clear during Run 1.

Fig. 3 shows the shape of the cable during Runs 6 and 7 on the 2-metre stramin net, depth meter and IKMT depressor on 23 August. On these runs the gear is presumed to have been fouled. Two soundings are shown at the very end of the cable for each run. These represent echoes from two parts of the gear, probably the rim of the net and the depressor. In this case the cable shape is slightly concave upward. The gear is probably behaving as any towed object in which the weight-drag ratio is less than that of the towing cable. Also shown are a few soundings on the cable during Run 1, 23 August, when the gear is presumed to have been towing properly. During this run the cable shape was probably the same as that when the complete IKMT was being towed.

It has been suggested to us by Mr. JOHN ISAACS, one of the designers of the IKMT, that the IKMT depressor should be very unstable when used without its net. This probably explains the observations in Runs 6 and 7 but the results of Run 1 show that this is not always so.

DEPTH-WIRE OUT RELATIONSHIP

The relationship between the length of the towing cable and the depth to the net from soundings on the IKMT itself is shown in Fig. 4. All soundings obtained are

plotted but the minimum soundings are used to draw the line. The relationship is also shown that would obtain if the depth were computed from the wire angle read at the surface during the runs ($67^\circ \pm 2$ from the vertical). The latter values are about 6% higher than the former. These curves would lie even closer together if an

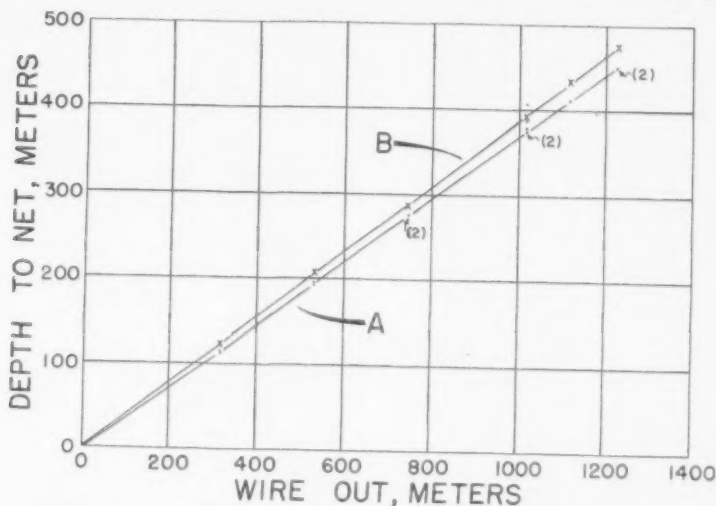


Fig. 4. A. Relationship between depth of 10-foot IKMT and length of towing cable at about 2.5 knots as observed by echo sounder. Figures in parentheses indicate number of observations at a particular point where more than one. B. Same relationship as in A. Computed from wire angle at surface.

error in the echo sounder, of the mechanical sort earlier described, of up to 6% existed. If the error exceeded 6% (a maximum of 10% seems reasonable) the actual depth would exceed the computed depth by some small amount (up to about 4%).

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REFERENCES

- DOW, W. (1954), Underwater telemetering. A telemetering depth meter. *Deep-Sea Res.*, **2**, 145-151, 9 figs.
- LEAVITT, B. B. (1935), A quantitative study of the vertical distribution of the larger zoöplankton in deep water. *Biol. Bull.*, **68** (1) 115-130, 3 figs.
- LEAVITT, B. B. (1938), The quantitative vertical distribution of macrozoöplankton in the Atlantic Ocean basin. *Biol. Bull.* **74** (3) 376-394, 5 figs.
- SCRIPPS INSTITUTION OF OCEANOGRAPHY (1953), Isaacs-Kidd midwater trawl. *SIO Ref.* 53-3 18 pp., 11 figs., 3 pls.
- WOOD, H. and PARRISH, B. B. (1951), Echo sounding experiments on fishing gear in action. *J. Cons. Explor. Mer.* **17** (1) 25-36, 7 figs.

On the vertical distribution of the dissolved oxygen in the ocean

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(Received 23 February 1956)

Abstract—Assuming that about 90 per cent of the oxygen consumption in sea water can be attributed to the oxidation of organic carbon to carbon dioxide, the amount of carbon dioxide calculated from the oxygen consumption (ΔC) was subtracted from the total amount of carbon dioxide present at two stations in the north-east Pacific. Upon dividing the remainder by the chlorosity, a nearly constant value was found from the surface to about 2,000 metres, giving weight to the validity of the assumption.

Seasonal variations in the integrated oxygen consumption in the water column to 1,000 metres were then compared with similar variations in the volumes of plankton taken from the upper 100 metres at two stations in the western Pacific. These values were found to vary similarly throughout the year.

These results, and the observations of other authors that the oxygen minimum occurs at nearly the same density in much of the ocean, lead to the conclusion that local productivity and the vertical distribution of density are important factors in determining the vertical distribution of dissolved oxygen and in accounting for the occurrence of minimum oxygen concentrations at intermediate depths.

1. INTRODUCTION

THE existence of the oxygen minimum layer in the sea is one of the interesting problems in oceanography. WÜST (1936) and DIETRICH (1937) considered that in the oxygen minimum layer there might be a minimum supply of oxygen by dynamical processes; therefore, the layer must be motionless. SEIWELL (1937) pointed out that the oxygen minimum layer is mainly caused by biochemical oxidation in the sea and showed that its occurrence may be possible even when there is an appreciable current in the layer.

SVERDRUP (1942) discussed the possible cases of equilibrium between the dynamical supply and the biochemical consumption at the oxygen minimum layer. According to his conclusion, the occurrence of the oxygen minimum is to be attributed mainly to the vertical variation in the rate of biochemical consumption of oxygen and the distribution of organic matter, rather than to dynamical processes. WATTENBERG (1939) emphasized the rôle of biochemical consumption of the oxygen and pointed out that the existence of a "Sprungschicht," or discontinuity layer, is the important cause of the oxygen minimum layer. He noticed also that the maximum concentrations of phosphate and silicate are generally found just below the oxygen minimum layer.

REDFIELD (1942) studied the distribution of the dissolved oxygen and phosphate in the Atlantic Ocean and concluded that a large part of the phosphate and the oxygen utilization may be attributed to characteristics of the water when it was relatively near the sea surface in high latitudes. However, in the tropical regions a large part of the phosphate excess and the oxygen deficit must be caused by the decomposition of organic matter which has sunk from the sea surface.

It is to be noticed that SEIWELL (1937, 1938), KAWAMOTO (1955) and RICHARDS and REDFIELD (1955) found that the oxygen minimum layers in both the Atlantic

and the Pacific Oceans occur most frequently along the same density surface of about $\sigma_t = 27.2$ to 27.3 .

RAKESTRAW (1947) observed the rate of consumption of oxygen in waters collected from the surface, the minimum oxygen layer and the deep layer, keeping the temperature constant for a long period, and showed that there is little consumption of the oxygen in either the minimum or the deep water for as long as nearly two years. On the other hand, surface waters kept at the lower temperature arrived at a level of oxygen concentration similar to that in the minimum samples after a comparatively short period of storage. RAKESTRAW suggested that the organic matter in the vertical water column, at least down to the oxygen minimum layer, is principally derived from the local surface.

The present authors tried to clarify the cause of the vertical distribution of the oxygen in the sea and arrived at the conclusion that the oxygen deficit is closely related to the increase in carbon dioxide, and is principally the result of the oxidative decomposition of the organic matter which has been produced locally.

2. THE RELATION BETWEEN THE DISSOLVED OXYGEN AND THE TOTAL CARBON DIOXIDE IN THE SEA

It is well known that sea waters are practically saturated with dissolved nitrogen regardless of depth (RAKESTRAW and EMMEL, 1937, 1938; THOMPSON and HAMM, 1941). Therefore, the dissolved oxygen might also be saturated if there were no

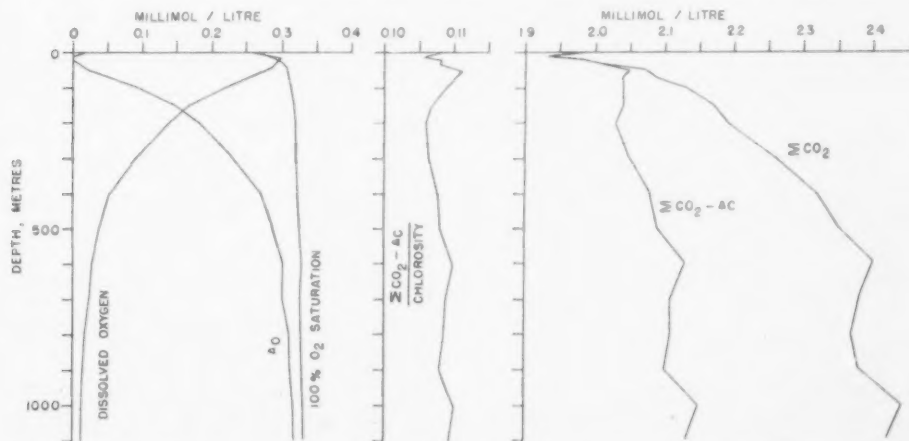


Fig. 1. Vertical distribution of dissolved oxygen and carbon dioxide, $54^{\circ}10'N$, $134^{\circ}10'W$ (from THOMPSON and HAMM, 1938).

biochemical oxygen consumption in the sea. The oxygen is mainly consumed by oxidizing reactions, both biological and chemical, of organic matter, producing the equivalent amount of the carbon dioxide, nitrate and phosphate. According to SVERDRUP *et al.* (1942, p. 234), atomic ratios of C : N : P in marine plankton are 106 : 16 : 1, on an average. Therefore, roughly speaking, about ninety per cent of all the utilized oxygen may be attributed to the oxidation of the organic carbon into the carbon dioxide.

As to the vertical distribution of the total carbon dioxide in the sea, we have the study carried out by THOMPSON and HAMM (1941) in the northeastern Pacific. Assuming that the oxygen was in a saturated state at the beginning, the difference (ΔO) between the saturated and the observed amount of oxygen was calculated using the data of THOMPSON and HAMM. As mentioned above, $0.9 \times \Delta O$ (mg atoms per litre) might be approximately equal to the increase of the carbon dioxide (ΔC) which was produced by the oxidative decomposition of organic matter.

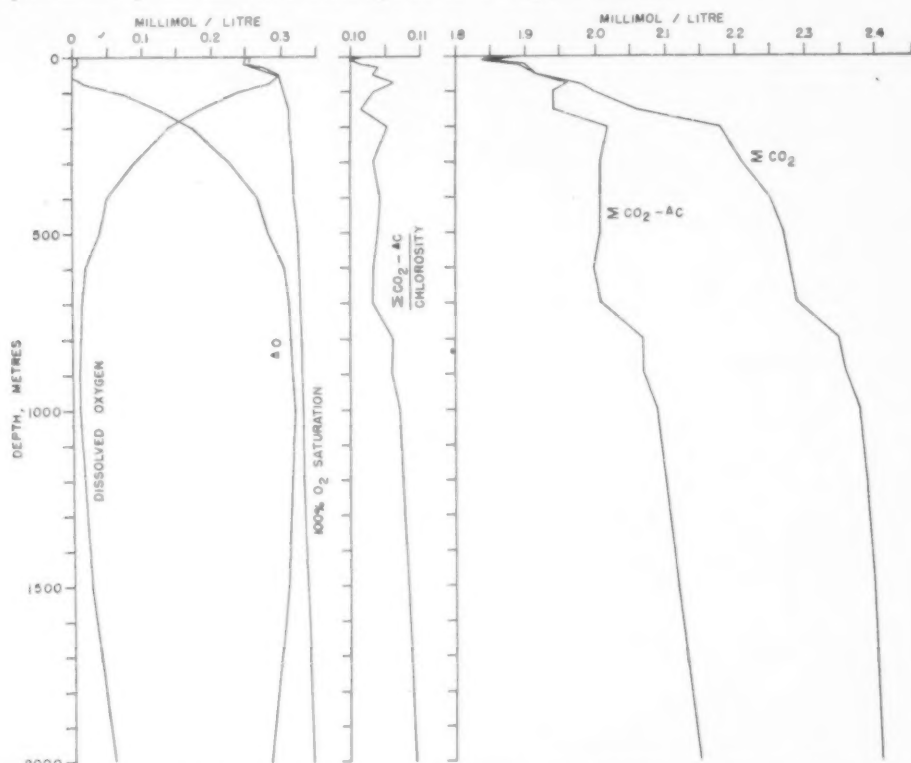


Fig. 2. Vertical distribution of dissolved oxygen and carbon dioxide, 48°24'N, 127°02'W (from THOMPSON and HAMM, 1938).

The difference, ΔC , was subtracted from the total amount of the carbon dioxide at each corresponding layer, and the remainder was divided by the chlorosity. As shown in Fig. 1 and Fig. 2, it is interesting that, like other major chemical elements in sea water, a nearly constant value of the ratio of carbon dioxide to chlorosity was obtained. There is, however, a slight increase in the ratio with increasing depth which may be attributed to the dissolution of the calcium carbonate of sinking shells. These results show that the greater part of the increase with depth of the carbon dioxide as well as the alkalinity, is caused by the organic matter rather than the dissolution of the calcium carbonate, as previously suggested by MOBERG and REVELLE (1937).

In the oxidation of organic matter, not only can carbonic acid be formed, but bicarbonate and carbonate as well, because, as is known, the organic matter in the sea contains a considerable amount of alkali, alkaline earth, and other kinds of metals (VINOGRADOV, 1953).

3. THE VERTICAL DISTRIBUTION OF DISSOLVED OXYGEN AND THE LOCAL POPULATION OF PLANKTON

It is to be noticed that almost all of the oxygen-poor areas are located in those parts of the ocean with high productivity, unless strong vertical convection prevails, as in the Arctic and Antarctic regions. This suggests that the amount of dissolved oxygen in the sea is intimately related to the local productivity in the area.

Therefore, we should be able to determine the correlation between the seasonal change of planktonic population and the dissolved oxygen in the same area. To do this, the seasonal variation of the integrated oxygen consumption in the water columns from the surface down to 1,000 m at two different points, respectively at 39°N, 153°E and 27°N, 135°E, was calculated. The former is a highly productive area in the Oyashio, and the latter a less productive area in the Kuroshio (Japan, Central Meteorological Observatory, Tokyo, 1954).

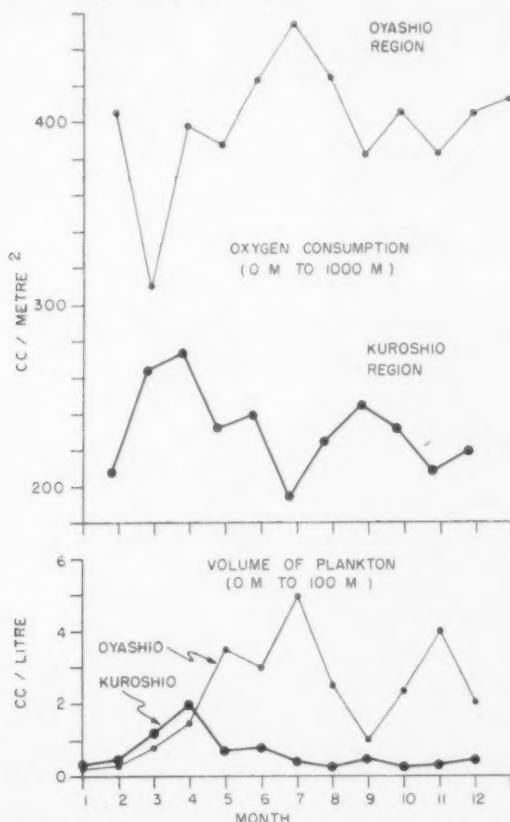


Fig. 3. Annual variation of oxygen consumption in the sea and settling volume of plankton (1952).

As shown in Fig. 3, the annual variations of the integrated oxygen consumption in the water column down to 1,000 m in each area coincide well with those of the "settling-volumes"* of plankton (cc/m³) living in the surface layer (0 to 100 m),

* Plankton samples were collected with KITAHARA's quantitative net (Hensen type, 22.5 cm mouth dia., xx 13, bolting silk) in vertical hauls. The volume was obtained by the settling method in graduated cylinders allowing the plankton to settle for 24 hours after fixation with formaldehyde solution.

which were observed by MARUMO *et al.* (1954). Moreover, the amount of oxygen consumption seems approximately proportional to the volume of plankton in each area.

These facts apparently show that the sinking and the oxidative decomposition of dead plankton occur in comparatively short periods of time. Thus it may be said with some confidence that the amount of oxygen utilized is one of the local and seasonal properties of the ocean.

As previously mentioned, the oxygen minimum layer appears most frequently at the water layer with the density of about $\sigma_t = 27.2$ to 27.3 . This suggests a relation between the falling velocity of detritus and its average density, where the latter approaches 1.027 there will be an accumulation at a certain depth, followed by a comparatively rapid rate of oxidation.

On the other hand, we should consider the possibility that lateral mixing easily takes place along the isodensity surfaces and that this may maintain the position of the oxygen minimum layer by lateral mixing.

4. CONCLUSION

As a result of the study, the present authors arrived at the conclusion that essential factors determining the vertical variation of dissolved oxygen and the occurrence of the oxygen minimum layer are the local productivity and the vertical density distribution of subsurface waters. By the latter, the depth of the oxygen minimum layer is determined, and by the former the extent of the oxygen deficit, and the generation of carbon dioxide.

On the other hand, one can compare the level of biological productivity by calculating the integrated oxygen consumption in water columns down to a certain depth in different areas and seasons. The increase in the total carbon dioxide as well as the alkalinity is caused mainly by the oxidation of organic matter. The increase of the total carbon dioxide gradually lowers the pH of deeper waters which probably promotes the gradual dissolution of calcium carbonate.

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REFERENCES

- DIETRICH, G. (1937), Über Bewegung und Herkunft des Golfstromwassers. *Veröff. Inst. für Meereskunde (n.f.)* (A), No. 33, Teil 2, 53-91.
Japan, Central Meteorological Observatory, Tokyo (1954), The results of marine meteorological and oceanographical observations. Nos. 11, vi + 362 pp., *Ibid.*, No. 12, viii + 138 pp.
KAWAMOTO, T. (1955), On the distribution of the dissolved oxygen in the Pacific Ocean, Part I. *U.M.I. to Sora*, Kobe Marine Obs., 32, 23-37 (in Japanese).
MARUMO, R., KITOU, M., and ASAOKA, O. (1954), The productivity and its seasonal variations of main plankton groups in the open sea. *J. Oceanogr. Soc. Japan*, 10, 209-215 (in Japanese).

- MOBERG, E. G. and REVELLE, R. R. (1937), The distribution of dissolved calcium in the North Pacific. *Int. Assoc. Phys. Oceanogr. (I.U.G.G., Assn. d'Océanogr. Phys.) Proc.-Verb.*, No. 2, p. 153.
- RAKESTRAW, N. W. (1937), Oxygen consumption in sea water over long periods. *J. Mar. Res.*, **6**, 259-263.
- RAKESTRAW, N. W. and EMMEL, V. M. (1937), The determination of dissolved nitrogen in water. *Ind. Eng. Chem., Anal. Ed.*, **9**, 344-346.
- RAKESTRAW, N. W. and EMMEL, V. M. (1938), The ratio of dissolved oxygen to nitrogen in some Atlantic waters. *J. Mar. Res.*, **1**, 207-216.
- REDFIELD, A. C. (1942), The processes determining the concentration of oxygen, phosphate and other organic derivatives within the depths of the Atlantic Ocean. *Pap. Phys. Oceanogr. Meteorol.*, **9** (2), 1-22.
- RICHARDS, F. A. and REDFIELD, A. C. (1955), Oxygen-density relationships in the western North Atlantic. *Deep-Sea Res.*, **2**, 182-199.
- SEIWELL, H. R. (1937), The minimum oxygen concentration in the western basin of the North Atlantic. *Pap. Phys. Oceanogr. Meteorol.*, **5** (3), 1-24.
- SEIWELL, H. R. (1938), Application of the distribution of oxygen to the physical oceanography of the Caribbean Sea region. *Ibid.*, **6** (1), 1-60.
- SVERDRUP, H. U. (1938), On the explanation of the oxygen minima and maxima in the ocean. *J. Cons.*, **13**, 163-172.
- SVERDRUP, H. U., JOHNSON, M. W., and FLEMING, R. H. (1942), *The Oceans*, Prentice-Hall Co., N.Y., x + 1087 pp.
- THOMPSON, T. G. and HAMM, R. E. (1941), Dissolved nitrogen in the sea water of the Northeast Pacific with notes on the total carbon dioxide and the dissolved oxygen. *J. Mar. Res.*, **4**, 11-27.
- VINOGRADOV, A. P. (1953), Elementary composition of marine plankton. In: The elementary chemical composition of marine organisms. *Mem. Sears Found. Mar. Res.*, Chap. 3, 130-146.
- WATTENBERG, H. (1939), Die Entstehung der Sauerstoffarmen Zwischenschicht im Ozean. *Ann. d. Hydrogr. u. Maritim. Meteor.*, **67**, 257-266.
- WÜST, G. (1936) Schichtung und Zirkulation des Atlantischen Ozeans. Teil 2: Die Stratosphäre. *Wiss. Ergeb. Deutschen. Atlant. Exped. "Meteor," 1925-1927* **6** (1), Teil 1, 180 pp.

Periodic variation of sea level induced by equatorial waves in the easterlies

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(Received 26 March, 1956)

Abstract—Sea-level observations at Canton Island show a regular four-day oscillation which is related to the passage of equatorial waves in the easterly winds over the island. Visual sea-level observations at Ocean Island show evidence of the same phenomenon. Records from tide gauges situated on other nearby islands show no such regular record. This gives an indication of the geographical extent of the perturbation of sea level.

INTRODUCTION

DURING a study of the day to day variation of sea level simultaneous tide records throughout a three-month interval from most of the permanent tide gauges maintained by the U.S. Coast and Geodetic Survey in the Pacific were examined (GROVES, 1956). Typical values of the root mean square deviation from the mean of these records (for spectral components having periods between two days and a week) are about 5 or 10 cm. The direct effect of the atmospheric pressure according to the "inverted barometer" law accounts for 50% to 75% of the activity in these periods.

At Canton Island, the three-month record showed a very regular oscillation which was coherent for 23 consecutive periods (Fig. 1). The amplitude (half the range) was about 3 cm on the average, and the period was 3.84 ± 0.02 days. The study was subsequently extended for 16 additional months, and during that time the oscillation was not as regular as in the original three-month record. Nevertheless, a prominent four-day oscillation was often present.

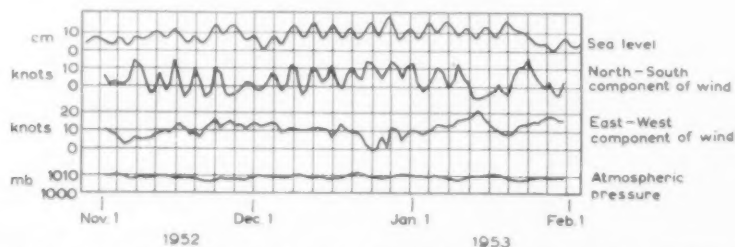


Fig. 1. Simultaneous records of sea level, surface atmospheric pressure and surface wind at Canton Island. The sea-level record is from position "A" (see Fig. 4). The wind and pressure records consist of (centred) averages of the eight observations made each day at three-hour intervals. The vertical lines in the figure are spaced every 3.84 days to demonstrate the remarkable coherence of phase throughout many cycles of the oscillation.

Sea-level records based on visual tide-staff observations were obtained from Ocean Island, Butaritari, and Tarawa (Fig. 2). There appears to be considerable three-to four-day activity in the Ocean Island record which may be related to the waves in the easterlies. The records from Butaritari and Tarawa appear much more irregular. At all other locations indicated by black dots in Fig. 3, there was no striking three- or four-day oscillation noted.

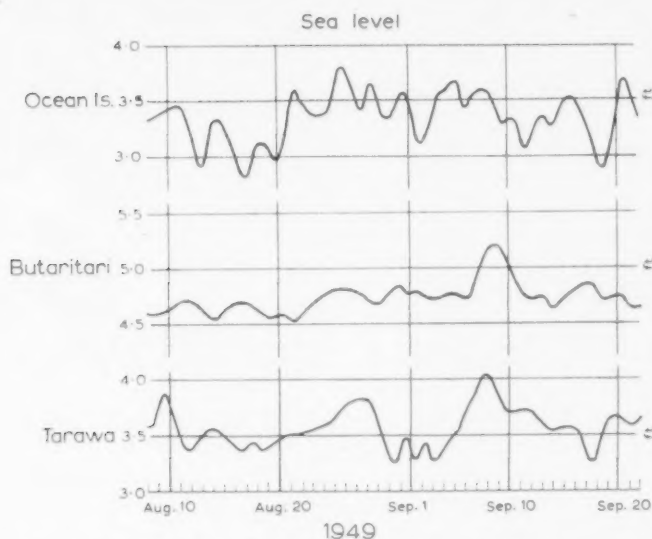


Fig. 2. Sea-level records at Ocean Island, Butaritari and Tarawa deduced from visual (tide staff) observations.

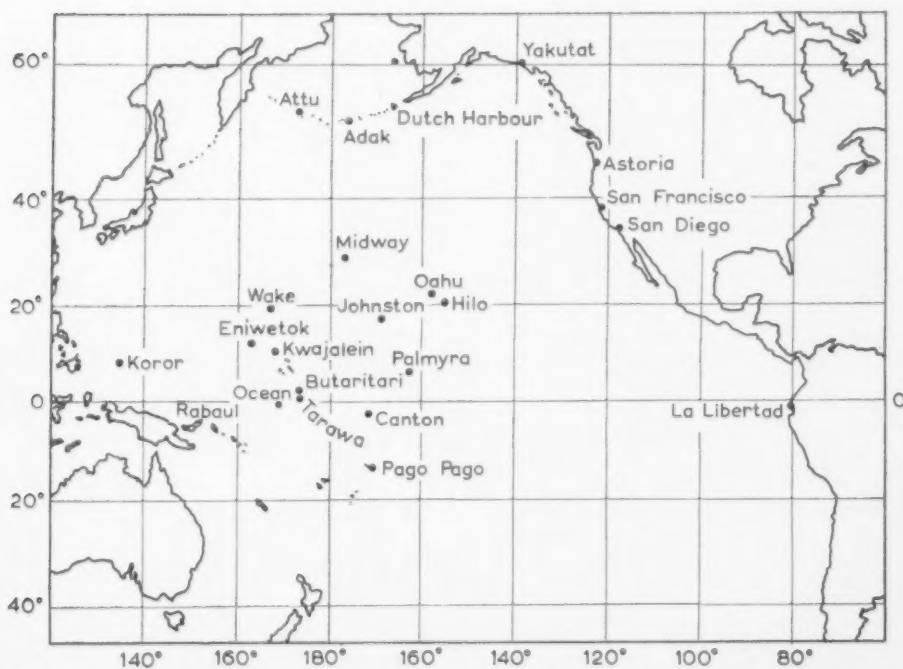


Fig. 3. Map of Pacific Ocean area. Black dots indicate most of the places from which sea-level records in the Pacific area were studied.

THE SEA-LEVEL RECORDS

The diurnal and semidiurnal tidal constituents were eliminated from the tide-gauge data of Fig. 1 by taking appropriate weighted averages of the hourly tidal heights. The symbol C_{51} merely designates a particular weighted average used in this study, and the method has been described (GROVES, 1955). The effect has been essentially to eliminate all components whose periods are less than 24 hours while retaining those of longer periods (i.e., a low pass filter), and the result can be conveniently referred to as "sea level."

The tide gauge from which the sea-level record of Fig. 1 was obtained is located within the lagoon of Canton Island at position "A" (Fig. 4). This lagoon is very large and communicates with the ocean only through two very small channels. However, a tide gauge was installed outside of the reef at position "B" in November, 1955, and a comparison of the sea-level records in and out of the lagoon was made. The records appeared identical with respect to the four-day oscillation of sea level, even though the diurnal and semidiurnal tides were markedly different. Tide measurements made by the U.S. Navy outside the reef at position "C" in 1944 before any gauge was placed in the lagoon also show evidence of the four-day oscillation.



Fig. 4. Map of Canton Island showing : A, the location of the U.S. Coast and Geodetic Survey's tide gauge ; B, the location of a water-level recorder installed November 1955 ; and C the location of a tide gauge temporarily installed by the U.S. Navy in 1944.

The sea-level records of Fig. 2 were obtained from the Hydrographic Office of the British Admiralty and consist of the means of the four tidal extrema (from visual observation) of each lunar day.

RELATION OF SEA LEVEL TO WIND

A detailed discussion of the equatorial waves is given by PALMER (1952). According to PALMER, these waves develop somewhere in the great void between the Line Islands and the Galapagos and progress westward at about 11 knots, becoming unstable and

shedding vortices (which sometimes attain hurricane intensity) after they pass the Gilbert Islands. Their wavelength is approximately 15° longitude. At any fixed (geographical) position in their path, then, a wind oscillation whose period is approximately four days will be observed.

Comparison of surface wind and pressure data with the sea-level record at Canton Island for November, 1952 to January, 1953 reveals a convincing correspondence between oscillations of sea level and of wind (Fig. 1). The pressure fluctuations are too small to have an important direct effect on the ocean. The large oscillation of the north component of the surface wind is approximately in phase with sea level. Periodogram analysis (Fig. 5) for a 3.84 day period shows that the sea-level oscillation leads the oscillation of the north component of the surface wind by about 7 hours, on the average. In Fig. 1, the sea-level oscillation appears more regular than the wind oscillation. This effect is not entirely the result of the difference of methods in treating the sea-level and wind data.

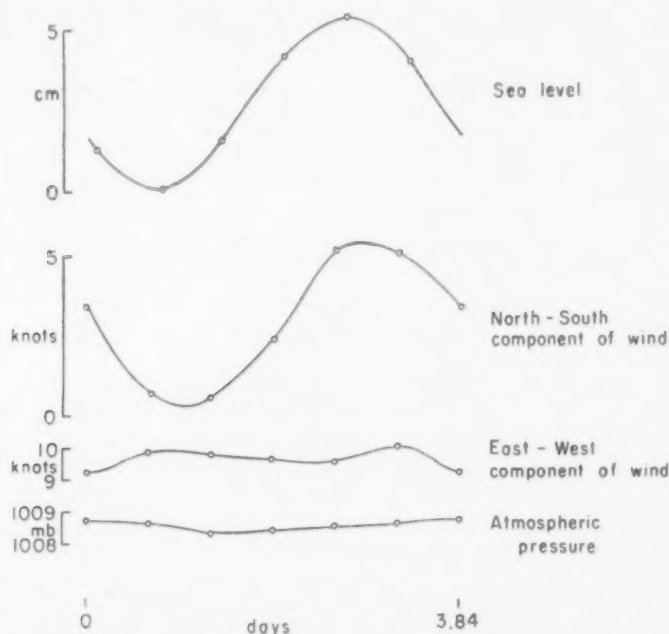


Fig. 5. Periodogram analysis of the variables shown in Fig. 1 carried out over 23 consecutive periods of 3.84 days, showing the average relative phase during this time.

CONCLUSIONS

The foregoing evidence indicates that the observed sea-level fluctuations at Canton Island are coupled to progressive waves in the easterly winds. The greater regularity of the sea-level oscillation may be the result of a free period (as yet undiscovered) in this region of the ocean very near four days, which is in forced resonance with the wind wave. Alternatively, the integrated wind stress over a large area of the ocean may oscillate in a regular fashion and be responsible for the sea-level oscillation.

One might expect that there would exist an oceanic wave of similar general character and geographic extent to the wave in the easterlies. If this were the case, the oceanic

wave would extend from about 140°W to about 160°E and have a fairly restricted north-south extent. The only available data that may be contradiction to this hypothesis are the sea-level records from Butaritari and Tarawa in the Gilbert Islands, which do not show strong evidence of a four-day wave.

It is curious that the four-day waves seemingly skip the Gilbert Islands and reappear at Ocean Island. This may be the result of the following factors :

a. The Gilbert Island chain may present an obstacle to the four-day ocean wave, which must reform west of the Gilberts to appear at Ocean Island.

b. Both Butaritari and Tarawa may be too far north to be in the path of the ocean wave. Of course, the ocean currents of the equatorial system and the position of their boundaries must play a very important role in the dynamics of these ocean waves.

The recently-installed tide gauge at Christmas Island should give interesting information concerning this four-day oscillation.

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REFERENCES

- GROVES, G. W. (1955), Numerical filters for discrimination against tidal periodicities, *Trans. Amer. Geophys. Union* **36** (6), 1073-1084.
GROVES, G. W. (In press), Day to day variation of sea level, *Meteorol. Monogr.*
PALMER, CLARENCE E. (1952), Tropical meteorology, *Q.J.R. Meteorol. Soc.*, **78** (336), 126-164.

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Proposed names of features on the deep-sea floor

3. Southern or Antarctic Ocean

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Abstract—The history of names in the Southern Ocean is discussed, followed by the names of those proposed by the British National Committee on the Nomenclature of Ocean Bottom Features. The selection is based on the Committee's published general principles governing the allocation of names.

INTRODUCTION

THE northern limit of the Southern or Antarctic Ocean is not precisely defined, but might well be regarded as the line of the Antarctic Convergence. This is a natural boundary, almost continuous around Antarctica, forming the northern limit of Antarctic surface water. Unfortunately the name Southern Ocean has not been officially adopted, and is omitted from the list of oceans and seas published by the International Hydrographic Bureau (1950, p. 4). On morphological grounds it is desirable to consider together all the features in the southern seas, instead of including them in the Atlantic, Indian and Pacific Oceans. The names Southern or Antarctic Ocean are, therefore, most useful from the standpoint of deep-sea morphology. An arbitrary northern limit of 52°S has been taken for the features described in this paper.

The first deep-sea sounding, in the Southern Ocean, 1560 fm. in 64° 38'S 173° 10'E, was taken by Capt. Sir JAMES CLARK ROSS (1847, 1, p. 170) on 30 December, 1840. A line, with swivels to prevent unlaying, was let out from a large reel on a ship's boat, whilst H.M. Ships *Erebus* and *Terror* were becalmed. In the early days of oceanographic exploration line soundings were taken in the Southern Ocean by H.M.S. *Challenger* (1872-76), S.S. *Belgica* (1897-99), S.Y. *Scotia* (1902-04) and the *Gauss* (1902-03), whilst more recently R.R.S. *Discovery II* (HERDMAN, 1932, and 1948) took systematic echo-soundings for many years.

Although the general shape of the major features in the Southern Ocean — three large basins separated by ridges and one trench — is known, no detailed survey has yet been made of any specific area. Extensive plains found in these basins would suggest horizontal transport of sediment, possibly by turbidity currents. A more detailed knowledge of morphology would be helpful in finding localities where there has been normal sedimentation on the deep-sea floor. Geochemical and biological investigations on cores from these areas would give valuable information about past temperature changes in the upper layers of the Southern Ocean, but practical difficulties of using coring apparatus in one of the stormiest oceans are likely to restrict the amount of material available. No seamount, or other small secondary feature, has yet been surveyed, and no attempt has been made to detach fossils from the sides of these features. Research on these lines might give useful information

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about the age of the Southern Ocean. The absence, over considerable distances, of any continental shelf around Antarctica, and the fact that where a shelf is found the edge is at a greater depth than elsewhere, present problems of more than passing interest. The morphological problems in the Southern Ocean are therefore diverse, and their solution would have bearing on the processes of sedimentation, the age of the Southern Ocean, the structure of its floor, and the origin of the Antarctic Continent. Agreed names, based on a rational system, would greatly facilitate discussion of these problems, and encourage the preparation of bathymetric charts, which would be of practical use to navigators. It is, therefore, hoped that during the Geophysical Year 1957-58, expeditions to Antarctica, as well as those which maintain permanent bases there, will include in their programme deep-sea morphological research.

HISTORY

The Burdwood Bank, which lies to the east of Staten I., was partially surveyed by Ross (1847, 2, p. 281 and 315). The name was derived from a supposed navigational hazard, the Burdwood Rock, which could not be found. The hazard was based on a report by Lt. T. BURDWOOD, agent in the *Kains* transport during her passage in November, 1828, from Rio de Janeiro to Valparaiso, of an islet in 54° 9'S 59° 36'W. MURRAY (1895, charts 1A-1C) gave brief consideration to nomenclature problems of the deep-sea floor. He allocated in an arbitrary way, personal and ships names. For the features known at that time in the Southern Ocean, MURRAY gave the names: South Georgia Plateau, Kerguelen Plateau, Barker Basin (a depression in the south-eastern Pacific), and the Ross Deep in the Weddell Sea. The Ross Deep was based on an erroneous sounding of 4000 fm. without reaching the bottom (Ross, 1847, 2, p. 363). Geographical names were given by SUPAN (1899) - e.g. the Kerguelen Trough and the Pacific-Antarctic Basin for the depression in the south-eastern Pacific. These were used in the first edition of the General Bathymetric Chart, which was approved at the Eighth International Geographical Congress in 1904. SCHOTT (1902), when describing the bathymetrical results of the German Deep-Sea Expedition, used the names Indian-Antarctic Basin and the Kerguelen Plateau. In view of the soundings taken by S.Y. *Scotia* in 1903 (BRUCE, 1905, p. 405) which showed that Ross's deep sounding was erroneous, MURRAY and HJORT (1912) renamed the Ross Deep the Valdivia Deep, after a sounding of 3134 fm. in 58° 5'S 35° 54'E, taken in 1898 by the *Valdivia*. The name Ross Deep was reallocated by MURRAY and HJORT to a depression north of South Georgia.

A great advance in deep-sea morphology was made possible by the introduction of the deep-water echo-sounder in the mid-1920's. The *Meteor* Expedition (1925-27) was the first to take advantage of this new technique, and PRATJE (1928) when describing the morphological work of this expedition in the South Atlantic used the name South Antilles Arc for the submarine connexion then postulated between Staten I. and Graham Land. This name had been proposed by KÜHN (1920) for the hypothetical submarine ridge, the existence of which had been suggested first by BELLINGSHAUSEN, after a visit to the South Sandwich Is. in 1819, and was more specifically postulated by SUESS (1909, 4, p. 488). In 1926 the *Meteor* Expedition discovered the South Sandwich Trench with a maximum depth of 4519 fm. in 55° 7.3'S 26° 46.5'W, as

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well as the Captain Spiess High (SPIESS, 1932, p. 185 ; MAURER and STOCKS, 1933, p. 171 and 174).

One of the outstanding bathymetric discoveries of the British-Australian-New Zealand Antarctic Research Expedition of 1929-31 on board S.Y. *Discovery* was the confirmation of a ridge extending in a southerly direction from Kerguelen, which had previously been inferred from deep-sea temperature measurements. This was called by MAWSON (1930) the Kerguelen-Gaussberg Ridge. A shallow sounding of 351 fm. on this ridge in $58^{\circ} 50'S$ $77^{\circ} 44'E$ (known by later writers on the work of this expedition as the Kerguelen-Antarctica Ridge) was called the Banzare Rise. Also a sounding south of Macquarie I. of 754 fm. in $56^{\circ} 40'S$ $158^{\circ} 39.2'E$ was called the Hjort Rise, after Dr. JOHAN HJORT, a former Director of Norwegian Fisheries (MAWSON, 1932 ; CAMPBELL, MOYES, and OOM, 1939). Atlantic-Indian Rise, Atlantic-Indian-Antarctic Basin, Indian-Antarctic Basin are features named on MAWSON's (1930) bathymetric chart.

The soundings taken during the four cruises of the *Norvegia* Expedition (1927-31) were an important contribution. In his description of the third cruise (1929-30) LARSEN (1930, p. 567) gave the name Gunnerus Bank to a sounding of 300 fm. in approximately $68^{\circ}S$ $32^{\circ}E$. The name was given in honour of Bishop GUNNERUS, who in 1770 described the pelagic shrimp. Both LARSEN's and MAWSON's bathymetric charts have the same names for the major features. During the *Norvegia's* last cruise a sounding of 656 fm. in $65^{\circ}00'S$ $2^{\circ}35'E$ was called the Maud Bank after AMUNDSEN's ship (ISACHSEN, 1932, p. 91). CHRISTENSEN named three banks in the Southern Ocean. Fram Bank (CHRISTENSEN, 1935, p. 50) lies with its western end about 50 miles north-westward of Cape Darnley and extends in an easterly direction for about 170 miles. It was discovered by S.S. *Thorshavn* in January, 1931, and named after NANSEN's famous ship. The least known depth is 76 fm. Gribb Bank, with a least known depth of 169 fm., lies approximately in $62^{\circ}S$ $88^{\circ}30'E$. The bank was found by S.S. *Thorshavn* in January, 1937, and named after the whale catcher *Gribb* (CHRISTENSEN, 1938, p. 7). Four Ladies Bank, over which the least known depth is 82 fm., lies approximately in $67^{\circ} 35'S$ $77^{\circ} 30'E$. The bank was found by S.S. *Thorshavn* on the 25th January, 1937 and was named in honour of the four ladies who accompanied the expedition (CHRISTENSEN, 1938, p. 8).

TAYLOR (1930, p. 160) considered that some of the shallower features on the Antarctic Chart, published in 1928 by the American Geographical Society, were terminal moraines - e.g. Davis Bank (west of Shackleton Ice Shelf), Mawson Bank (north of Adélie Coast), and Pennell Bank (north of Ross Ice Shelf). These names were given in honour of Capt. J. K. DAVIS, the commanding officer of S.Y. *Discovery* during her cruise of 1929-30 ; Sir DOUGLAS MAWSON the Australian authority on Antarctica, and Cdr. H. PENNELL, R.N., the commanding officer of the S.Y. *Terra Nova*.

In the years 1929-31 a more comprehensive bottom survey of the Scotia Sea was made by R.R.S. *Discovery II*, and the name Scotia Arc was given by HERDMAN (1932, p. 214) to the ridge which forms the northern, eastern and southern boundaries of this sea. HERDMAN rejected PRATJE's earlier name the South Antilles Arc on the grounds that it was misleading, because there are no South Antilles. LITTLEHALES (1932) in his account of the configuration of the ocean basins, gives brief reference to the South Sandwich Deep, the West Antarctic or Ross Basin, and the South-

Eastern Pacific Basin. To describe the morphology of the Atlantic sector of the Southern Ocean, STOCKS and WÜST (1935) used geographical names – e.g. South Antilles Arc, South Sandwich Trench, South Sandwich Ridge for some shallower soundings north-east of the South Sandwich Trench, and the Atlantic–Indian South Polar Basin. In a similar way SCHOTT (1935) used geographical names for the Indian Ocean sector of the Southern Ocean – e.g. Bouvet Ridge, Macquarie Ridge, South Pacific Cross Ridge, Indian–South Polar Basin, and the Bellingshausen Trough.

The soundings taken north of the Ross Sea by the second Byrd Antarctic Expedition, which left Boston in September, 1933, were worked up by ROOS (1937). The name Iselin Bank, in honour of Dr. C. O'D ISELIN of Woods Hole Oceanographic Institution, was given to a shallower feature south of Scott I. with a minimum depth of 383 fm. and separated from the continental shelf by a deep gully. Other features noted on ROOS's chart are: Easter Rise, Pennell Bank, and the Pacific–Antarctic Basin.

The desirability of a geographical basis for nomenclature was stressed by WÜST (1936). In a paper dealing with the division of the oceans, the following names are used: Eastern Pacific Ridge, Atlantic–Indian–South Polar Basin, East Indian–South Polar Basin, and Pacific–South Polar Basin. Four years later WÜST (1940a and 1940b) again stressed this principle in his report to the International Nomenclature Committee. His proposed names were the same as before, with the single exception that the Atlantic–Indian–South Polar Basin was divided into two (Atlantic–South Polar Basin and the West Indian–South Polar Basin).

The first attempts to consider the features in the Southern Ocean as a morphological unit were made by MACKINTOSH (1940) and MOSBY (1940). Both authors supported geographical names. MOSBY urged, in addition, that names such as Ross Deep, Valdivia Deep and Barker Basin, should not be used although established in the early days of oceanography. The name Scotia Arc was favoured by MACKINTOSH, whilst MOSBY – to avoid the difficulty of deciding between this and the rival name South Antilles Arc – suggested that it should be called the South Atlantic Arc. The ridge extending in an easterly direction from the southern extremity of the Mid-Atlantic Ridge was divided, and called by MOSBY the Bouvet Ridge and the Atlantic–Indian Swell, whilst MACKINTOSH used the name Atlantic–Indian Cross Ridge. The name Kerguelen–Gaussberg Ridge was used by both authors. MOSBY made three proposals for the ridge in the Southern Pacific – namely Antarctic–Pacific Ridge, South Pacific Ridge, and the Easter Island Rise – whilst MACKINTOSH favoured Cape Adare–Easter Island Ridge. Eastern Indian Swell, Macquarie Ridge, and the South Sandwich Swell were recognized by MOSBY, as well as the Atlantic–Indian–Antarctic Basin, the Eastern Indian–Antarctic Basin, and the Pacific–Antarctic Basin. MACKINTOSH, whilst agreeing with the name of the last basin, suggested for the other two the Atlantic–Antarctic Basin and the Australian–Antarctic Basin.

Barth Bank, over which there is a reported depth of 71 fm. in 62° 52'S 41° 14'W, first appeared on British Admiralty Chart No. 3176 in 1941. The bank was inserted on the basis of a Norwegian Chart dated 1938. Since soundings taken by the whale factory ship *Walter Rau* exceeded 1641 fm. at this position, and deep soundings were found between here and the wide shallow shelf south of the South Orkneys, HERDMAN (1948, p. 68) considered that, if the Barth Bank exists, it must be an isolated feature. The Hydrographic Department (1948, p. 142) considers that its existence is doubtful.

SVERDRUP, JOHNSON and FLEMING (1942) recognized the following features in the Southern Ocean: Atlantic-Indian-Antarctic Basin, Eastern Indian-Antarctic Basin, Pacific-Antarctic Basin, South Antilles Basin, and the South Sandwich Trench.

The principle of geographical nomenclature for major deep-sea features was adopted on the second edition of U.S.H.O. Chart 2562 (1947) - e.g. Atlantic-Indian Swell, Indian-Antarctic Swell, Easter Island Swell, Kerguelen-Gaussberg Ridge, Atlantic-Indian-Antarctic Basin, Indian-Antarctic Basin, Pacific-Antarctic Basin, and the South Sandwich Trench; but the old name Valdivia Deep was retained. For secondary features existing names were used - e.g. Hjort, Sars, and Spiess Seamounts; Banzare, Barth, Four Ladies, Fram, Gribb, Gunnerus, Iselin, Maud, Pennell, Rhine, and Scott I. Banks. All these names are non-geographical, with the exception of Scott I. Bank. On the third edition, published in 1955, the names of seamounts and banks have been retained, but the major features have been left unnamed. The U.S. Board on Geographic Names (*Special Publication*, No. 86, 1947) recognizes the above mentioned banks with the exception of Banzare and Rhine Banks. It is, however, possible that these were excluded, because the northern limit of features described in this publication was apparently 60°S (AUROUSSEAU, 1948). Finally KOSACK¹ (1954) on his four bathymetric charts gives the names of nine banks (Davis, Barth, Four Ladies, Fram, Gunnerus, Iselin, Maud, Mawson, and Pennell).

GENERAL PRINCIPLES

Although the idea of geographical nomenclature for major features was first put forward by SUPAN in 1899, this principle has only recently been generally accepted. In view of this the "law of priority" does not apply, unless the existing name is in accordance with the rules of geographical nomenclature. It is very desirable that the chosen name should be brief and descriptive. Also, unless there are adequate reasons, features should remain unnamed. Secondary features should not be named unless they have been reasonably well surveyed. These may be named after a ship or person, provided that the chosen name has not been previously used, and that there is no suitable geographical alternative. In order to achieve internationally agreed names, careful consideration has been given by the British Committee to general principles (WISEMAN and OVEY, 1955).

PROPOSED NAMES

Proposals for names in the Southern Ocean were first considered by the British Committee in December, 1950, and, after consultation with outside experts, the names have been revised from time to time. At a meeting on 13 December, 1955, the Committee approved the list of names given below, and recommended that it should be published in view of the great interest in Antarctic research. The Committee would like to be kept informed of newly discovered deep-sea features which have been surveyed. In view of the published principles, only brief remarks are necessary about two of the selected names. The Scotia Ridge is named after the Scotia Sea, as it forms the northern, eastern, and southern margin of that sea. The name South Antilles Arc has been rejected, because firstly, the name is confusing and secondly, the South Antilles Sea is not a generally accepted name. MOSBY's (1940, p. 96) alternative name the South Atlantic Arc does not give any clear indication of its position. The Atlantic-Antarctic Ridge extends in an easterly direction from about

52°S 10°W to 52°S 24°E. It would seem to be a more descriptive name than the alternatives the Atlantic-Indian Cross Ridge, or the Atlantic-Indian Swell.

Only two names of secondary features (Maud Seamount and Burdwood Bank) are recognized by the Committee. The isolation of the Maud Seamount is reasonably well established by surrounding soundings taken by R.R.S. *Discovery II*, as well as other ships. Burdwood Bank is well surveyed (HERDMAN, 1948, pl. XXIII), and has a minimum depth of 16 fm. in 54° 08.5'S 59° 45'W (Admiralty Chart No. 2202B). The bank is probably a prolongation of the continental shelf, from which it is separated by a minimum depth of 258 fm. in 54° 26'S 62° 38'W. On its southern and north-eastern sides it rises from depths greater than 1600 fm. and 1000 fm. respectively. There is little morphological information about the other secondary features mentioned in the historical section. Many of these were originally named on the basis of a single line of soundings, and none of them has been surveyed. Consequently the British Committee considers that they should not be given names. Four of these features, rising at least 3000 ft. above the general level of the sea floor, have been given code numbers, and it is hoped that these interesting features will eventually be surveyed.

1. Ridges

1. *Atlantic-Antarctic Ridge*

A broad ridge rising from a general depth of 2000 fm. and extending with some gaps in an easterly direction from approximately 52°S 10°W to 52°S 24°E. New name proposed by British Committee. Bathymetric charts: General Bathymetric Charts B'_I (1952) and B'_{IV} (1954); SCHOTT (1944, pl. V); STOCKS and WÜST (1935, sheet 1); STOCKS (1937, sheet SII₂); U.S.H.O. Chart 2562 (1955).

2. *Kerguelen-Gaussberg Ridge*

A broad ridge rising from a general depth of 1400 fm. and extending in a south-easterly direction from Iles de Kerguelen to approximately 63°S 90°E. Name proposed by LARSEN (1930) and MAWSON (1930). Bathymetric charts: General Bathymetric Chart B'_{IV} (1954); SCHOTT (1935, pl. IV); U.S.H.O. Chart 2562 (1955). HERDMAN (1948, p. 94) gives a description of this ridge.

3. *Indian-Antarctic Ridge*

A broad ridge rising from a general depth of 2000 fm. and extending from about 50°S 120°E to the Balleny Is. Name proposed by SCHOTT (1902). Bathymetric charts: General Bathymetric Chart B'_{III} (1954); U.S.H.O. Chart 2562 (1955).

4. *Macquarie-Balleny Ridge*

A ridge extending, with some gaps, from Macquarie I. to Balleny Is. It joins the Indian-Antarctic Ridge at about 60°S. Name proposed by the British Committee. Bathymetric charts: General Bathymetric Chart B'_{III} (1954); U.S.H.O. Chart 2562 (1955). See also French Chart 6061.

5. *Pacific-Antarctic Ridge*

A broad ridge rising from a general depth of 2000 fm. and extending from about 40°S 112°W to 65°S 180°E. Name proposed by British Committee.

MOSBY (1940) proposed a similar name : Antarctic-Pacific Ridge. Bathymetric charts : SCHOTT (1935, pl. IV) ; U.S.H.O. Chart 2562 (1955).

6. *Scotia Ridge*

A general name given to the ridge which extends with some small gaps from Staten I. through Burdwood Bank, South Georgia, and the South Sandwich Is. to Graham Land. Name proposed by HERDMAN (1932, p. 214). The ridge is subdivided into Burdwood Bank (name proposed by ROSS in 1847), Burdwood - South Georgia Ridge, South Georgia - Sandwich Ridge, South Orkney - Sandwich Ridge, and the South Orkney - Graham Land Ridge. The latter four names have been proposed by the British Committee. Bathymetric charts : General Bathymetric Chart B'_I (1952) ; HERDMAN (1948, pls. XXIII and XXIV) ; SCHOTT (1944) ; STOCKS and WÜST (1935) ; U.S.H.O. Chart 2562 (1955).

2. *Seamount*

1. *Maud Seamount* 656/1500 fm. 65° 00'S 02° 35'E

Discovered in January 1931 by R.S. *Norvegia* and named after Amundsen's ship (ISACHSEN, 1932, p. 91). Admiralty Chart 3170 ; Bathymetric charts : General Bathymetric Chart B'_{IV} (1954) ; U.S.H.O. Chart 2562 (1955).

3. *Seahighs*

1. *SE 5920-7652 (b)*

Rises from a general depth of 1000 fm. to 102 fm. and is situated on the Kerguelen-Gaussberg Ridge. Formerly known as the Banzare Rise (MAWSON, 1932, p. 107 ; CAMPBELL, MOYÉS and OOM, 1939, p. 9). A seahigh in approximately 62°S 88° 30'E (formerly known as the Gribb Bank) may be connected with this feature. Admiralty Chart 3171 ; Bathymetric charts : General Bathymetric Chart B'_{IV} (1954) ; U.S.H.O. Chart 2562 (1955).

2. *SE 5614-15844 (m)*

Rises from a general depth of 1000 fm. to 446 fm., and is situated on the Macquarie-Balleney Ridge. A sounding of 815 m. was obtained by the *Commandant Charcot* in 1949. Formerly known as the Hjort Rise (Campbell, Moyes and Oom, 1939, p. 7). Bathymetric charts : General Bathymetric Chart B'_{III} (1954) ; U.S.H.O. Chart 2562 (1955).

3. *SW 5936-6857 (m)*

Rises from a general depth of 1500 fm. to 369 fm. Formerly known as the Sars Bank. Discovered in February, 1934, by S.S. *Thorshavn*, and named after the Norwegian scientists MICHAEL and OSSIAN SARS (AAGAARD, 1934, p. 840). Admiralty Chart 3175 ; Bathymetric charts : General Bathymetric Chart B'_I (1952) ; U.S.H.O. Chart 2562 (1955).

4. *SE 5444-0004 (m)*

Rises from a general depth of 1000 fm. to 225 fm. Sounding taken by the *Meteor*, profile V (MAURER and STOCKS, 1933, p. 174) and corrected for a speed of sound of 1455 m./sec. Formerly known as the Captain Spiess High. Admiralty Chart 2202A ; Bathymetric charts : General Bathymetric Chart B'_{IV} (1954) ; U.S.H.O. Chart 2562 (1955).

4. Basins

1. *Atlantic-Indian-Antarctic Basin*

Bounded on the north by the South Orkney-Sandwich Ridge, the Atlantic-Antarctic Ridge, the Prince Edward-Crozet Ridge, and on the east by the Kerguelen-Gaussberg Ridge. Name proposed by MAWSON (1930) and LARSEN (1930). Greatest depth 3211 fm., 5872 m., $58^{\circ}40'S$ $29^{\circ}30'E$. Echo-sounding taken by S.S. *Thorshavn* on 27th December, 1933, and corrected by MATTHEWS's (1939) tables. Bathymetric charts: General Bathymetric Chart B'_{IV} (1954); U.S.H.O. Chart 2562 (1955).

2. *Eastern Indian - Antarctic Basin*

Bounded on the west by the Kerguelen-Gaussberg Ridge, on the north by the Amsterdam-St. Paul Plateau, and on the east by the Indian-Antarctic Ridge. Name proposed by MOSBY (1940). SCHOTT's name (1902) was Indian-Antarctic Basin. Greatest depth 2983 fm., 5455 m., $54^{\circ}32'45''S$ $123^{\circ}05'00''E$. Echo-sounding taken by R.R.S. *Discovery II* on 24 May 1932, and corrected by MATTHEWS's (1939) tables. Bathymetric chart: General Bathymetric Chart B'_{III} (1954).

3. *Pacific-Antarctic Basin*

Bounded on the west and north by the Pacific-Antarctic Ridge and the South-eastern Pacific Plateau. Name proposed by SUPAN (1899). Greatest depth 3570 fm. 6414 m., $66^{\circ}58'S$ $176^{\circ}14'W$. Sounding corrected by MATTHEW's (1939) tables. The uncorrected sonic sounding was 3480 fm., taken with a velocity of 4800 ft./sec. Bathymetric chart: U.S.H.O. position plotting sheet "Scott I."

5. Trench

1. *South Sandwich Trench*

Situated on the east side of the South Sandwich Is. Extends from approximately $55^{\circ}S$ $32^{\circ}W$ to $61^{\circ}S$ $27^{\circ}W$, and is roughly defined by the 3000 fm. contour. Name proposed by SPIESS (1926, p. 226). Greatest depth - the *Meteor* Depth - 4519 fm., 8264 m., $55^{\circ}7.3'S$ $26^{\circ}46.5'W$. Sounding taken by the *Meteor* in February, 1926, and corrected for a velocity of 1517 m./sec. (MAURER and STOCKS, 1933, p. 171). The uncorrected sounding was 8118 m. with a velocity of 1490 m./sec. Bathymetric charts: General Bathymetric Chart B'₁ (1952); HERDMAN (1948, pl. XXIII); STOCKS (1937); STOCKS and WÜST (1935).

REFERENCES

- AAGAARD, B. (1934), *Fangst og forskning i Sydishavet*, 3. Gylendal Norsk Forlag, Oslo.
 AUROUSSEAU, M. (1948), The treatment of Antarctic Names. *Geogr. Rev.*, **38**, 487-490.
 BRUCE, W. S. (1905), Some results of the Scottish National Antarctic Expedition. *Scottish Geogr. Mag.*, **21**, 401-412.
 CAMPBELL, S. A. C., MOYES, M. H., and OOM, K. E. (1939), Soundings. *Repts. B.A.N.Z. Antarctic Research Expedition*, 1929-31, Ser. A, 3, pt. 1, 1-21.
 CHRISTENSEN, L. (1935), *Such is the Antarctic*. Hodder and Stoughton, London.
 CHRISTENSEN, L. (1938), *My last expedition to the Antarctic 1936-1937*. Johan Grundt Tanum, Oslo.
 HERDMAN, H. F. P. (1932), Report on soundings taken during the *Discovery* Investigations 1926-1932. *Discovery Repts.*, **6**, 205-236.
 HERDMAN, H. F. P. (1948), Soundings taken during the *Discovery* Investigations 1932-39. *Discovery Repts.*, **25**, 39-106.

- HYDROGRAPHIC DEPARTMENT (1948), *The Antarctic Pilot*. Admiralty, London.
- INTERNATIONAL HYDROGRAPHIC BUREAU (1950), Limits of Oceans and Seas. *Sp. Publ.*, No. 23, Monte-Carlo.
- ISACHSEN, G. (1932), Norwegian explorations in the Antarctic, 1930-1931. *Geogr. Rev.*, **22**, 83-96.
- KOSACK, H. P. (1954), Zur Vierblattkarte der Antarktis in 1 : 4 Millionen. *Petermanns Geogr. Mitt.*, **98**, 81-85.
- KÜHN, F. (1920), Der sogenannte Südantillen-Bogen und seine Beziehungen. *Zeit. der Ges. für Erdkunde*, 249-261.
- LARSEN, H. R. (1930), The *Norvegia* Antarctic Expedition of 1929-1930. *Geogr. Rev.*, **20**, 555-573.
- LITTLEHALES, G. W. (1932), The configuration of the oceanic basins. *Physics of the Earth - V. Oceanography*, 13-46. National Research Council, Washington D.C.
- MACKINTOSH, N. A. (1940), Nomenclature of the major divisions of the Southern Seas. *Assoc. d'Océanogr. Phys., Pub. Sci.*, No. 8, 93-94.
- MATTHEWS, D. J. (1939), *Tables of the velocity of sound in pure water and sea water for use in echo-sounding and sound-ranging*. H.D. No. 282, H.M. Stationery Office, London.
- MAURER, H. and STOCKS, T. (1933), Die Echolotungen des "Meteor." *Wiss. Ergebn. der Deutsch. Atlant. Exped. Forsch. und Vermess. "Meteor."* 1925-27, **2**, 1-309.
- MAWSON, D. (1930), The Antarctic cruise of the *Discovery*, 1929-1930. *Geogr. Rev.*, **20**, 535-554.
- MAWSON, D. (1932), The B.A.N.Z. Antarctic Research Expedition, 1929-31. *Geogr. J.*, **80**, 101-131.
- MOSBY, H. (1940), Nomenclature of the submarine features of the Southern Seas. *Assoc. d'Océanogr. Phys., Pub. Sci.*, No. 8, 95-99.
- MURRAY, J. (1895), A summary of the scientific results, (second part). *Rept. Sci. Results exploring voyage H.M.S. "Challenger,"* 1873-76.
- MURRAY, J. and HJORT, J. (1912), *The Depths of the Ocean*. Macmillan and Co., London.
- PRATJE, O. (1928), Beitrag zur Bodengestaltung des Südatlantischen Ozeans. *Centralbl. für Min., Geol. und Paläontol.*, Abt. B, 129-152.
- ROOS, S. E. (1937), The submarine topography of the Ross Sea and adjacent waters. *Geogr. Rev.*, **27**, 574-583.
- ROSS, J. C. (1847), *Voyage of discovery and research in the Southern and Antarctic Regions, during the years 1839-43*. Murray, London.
- SCHOTT, G. (1902), Océanographie und Maritime Meteorologie. *Wiss. Ergeb. der Deutsch. Tiefsee. Exped. auf dem Damp. "Valdivia,"* 1898-99, **1**, 1-403.
- SCHOTT, G. (1935), *Geographie des Indischen und Stillen Ozeans*. Boysen, Hamburg.
- SCHOTT, G. (1944), *Geographie des Atlantischen Ozeans*. Boysen, Hamburg.
- SPIESS, F. (1926), Bericht des Expeditionsleiters. *Zeit. der Ges. für Erdkunde*, 209-230.
- SPIESS, F. (1932), Das Forschungsschiff und seine Reise. *Wiss. Ergbn. der Deutsch. Atlant. Exped. Forsch. und Vermess. "Meteor,"* 1925-27, **1**, 1-442.
- STOCKS, T. (1937), Morphologie des Atlantischen Ozeans. Grundkarte der Ozeanischen Lotungen 1 : 5 Millionen, Blatt SII₂. *Wiss. Ergebn. der Deutsch. Atlant. Exped. Forsch. und Vermess. "Meteor,"* 1925-27, B.3, Tl. 1, Lief. 4 (1).
- STOCKS, T. and WÜST, G. (1935), Morphologie des Atlantischen Ozeans. Die Tiefenverhältnisse des Offenen Atlantischen Ozeans. *Wiss. Ergbn. der Deutsch. Atlant. Exped. Forsch. und Vermess. "Meteor,"* 1925-27, B.3, Tl. 1, Lief. 1, 1-32.
- SUESS, E. (1909), *The face of the Earth*, 4. Clarendon Press, Oxford.
- SUPAN, A. (1899), Die Bodenformen des Weltmeeres. *Petermanns Mitt. aus Justus Perthes' Geogr. Anst.*, **45**, 177-188.
- SVERDRUP, H. U., JOHNSON, M. W., and FLEMING, R. H. (1942), *The Oceans, their Physics, Chemistry and General Biology*. Prentice-Hall, Inc., New York.
- TAYLOR, G. (1930), *Antarctic Adventure and Research*. Appleton and Co., New York and London.
- WISEMAN, J. D. H., and OVEY, C. D. (1955), Proposed names of features on the deep-sea floor 2. General principles governing the allocation of names. *Deep-Sea Res.*, **2**, 261-263.
- WÜST, G. (1936), Die Gliederung des Weltmeeres. *Petermanns. Mitt.*, B. **82**, H.2, 33-38.
- WÜST, G. (1940a), Zur Nomenklatur der Grossformen der Ozeanböden. *Assoc. d'Océanogr. Phys., Pub. Sci.*, No. 8, 120-122.
- WÜST, G. (1940b), Vorschlag für die Namensgebung in der Tiefsee. *Assoc. d'Océanogr. Phys., Pub. Sci.*, No. 8, 123-124.

Two recently discovered features on the floor of the Indian Ocean Andrew Tablemount and David Seaknoll

JOHN D. H. WISEMAN AND Cdr. G. P. D. HALL, D.S.C., R.N.

Abstract—The results of recent surveys of Andrew Tablemount with a least depth of 850 fm. in $06^{\circ} 45.3'N$, $50^{\circ} 29.5'E$, and David Seaknoll with a least depth of 935 fm. in $06^{\circ} 23.5'N$, $50^{\circ} 14.75'E$, are given. The basis of the survey of Andrew Tablemount was a radar-reflecting beacon anchored at a depth of 870 fm. in $06^{\circ} 48.2'N$, $50^{\circ} 27.1'E$. The survey of David Seaknoll was carried out by dead reckoning (adjusted for a set of 0.56 knots in a 263° direction), because the radar-reflecting beacon failed to withstand a gale.

INTRODUCTION

In April 1954 H.M.S. *Dalrymple* (Acting Cdr. J. T. K. PAISLEY, R.N.) was on passage from Aden to Zanzibar and running a line of deep soundings in accordance with normal practice. In position $06^{\circ} 47'N$, $50^{\circ} 26'E$, soundings shoaled from a steady depth of about 1,640 fm. to an elevation of 920 fm. Approximately 20 miles further on the soundings again shoaled from a depth of over 1,300 fm. to an elevation of 949 fm. in $06^{\circ} 24'N$, $50^{\circ} 16'E$. There was not time to turn back to examine these seahighs and only a preliminary report was rendered on them. In accordance with the recommendations of the British National Committee on the Nomenclature of Ocean Bottom Features (WISEMAN and OVEY, 1955) these two seahighs were given the following code numbers: NE 0647-5026 (m) and NE 0624-5016 (k). Fig. 1 shows the general location of these seahighs as now charted, and Fig. 2 shows their outline in more detail together with a selection from the line of soundings made by *Dalrymple*, and existing soundings from Admiralty Chart No. 2953.

SURVEYS

In order that more might be learnt about the shape and extent of these features, H.M.S. *Dalrymple* was instructed to investigate them in detail on her return passage to Aden in January 1955. A beacon, which withstood a gale, was anchored on the more northerly feature in a depth of 870 fm. The position of the beacon, $06^{\circ} 48.2'N$, $50^{\circ} 27.1'E$, was obtained astronomically. Using radar ranges and visual bearings by day, with radar bearings at night, it was possible to complete within 20 hours a reasonably comprehensive survey. The feature has a more or less circular flat top (Figs. 3 and 4) with a least depth of 850 fm. in $06^{\circ} 45.3'N$, $50^{\circ} 29.5'E$. A comparatively steep slope with a maximum gradient of 23° occurs on the northwestern side of the feature. It is clear from Fig. 3, taken in conjunction with previous soundings in this neighbourhood (Fig. 2), that on its east side this seamount rises from depths of 2,400 fm., and elsewhere the summit is 3,000 ft. or more above its base. In view of the depth of the least sounding, the height of the feature above its base, and its relatively flat top which within the 1,000 fm. contour extends for a distance of 13 by 14 miles, the feature is classed as a tablemount (WISEMAN and OVEY, 1953, p. 15). For lack of a suitable geographical name, and because the ship's name and the Captain's name have been used elsewhere, it is proposed to call this feature by the Christian

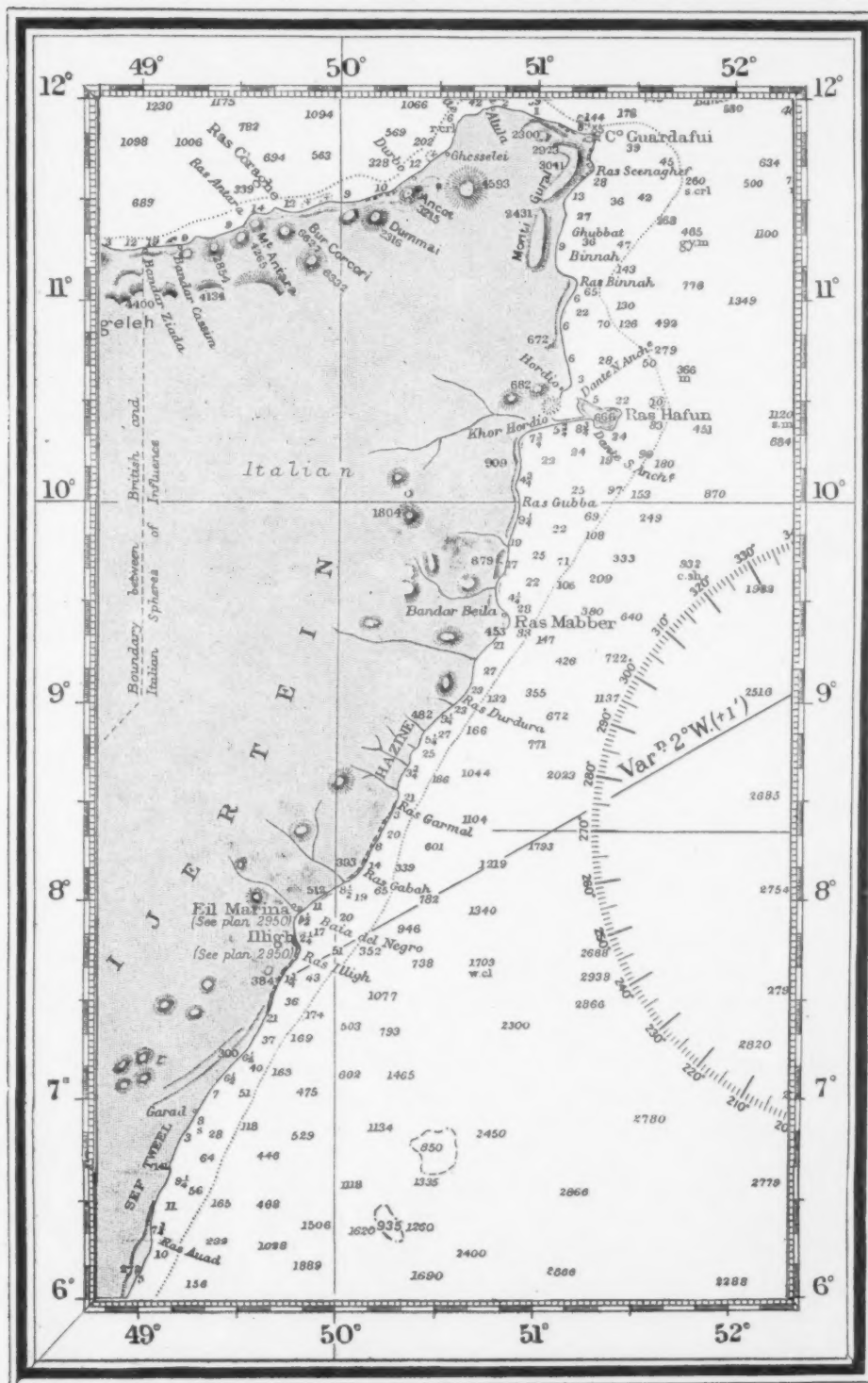


Fig. 1. Portion of Admiralty Chart No. 597 showing location of Andrew Seamount and David Seaknoll.

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name of the officer primarily associated with its survey – the navigating officer – and name it Andrew Tablemount. This proposal has the concurrence of the British National Committee on the Nomenclature of Ocean Bottom Features.

Two samples of globigerina ooze were obtained from Andrew Tablemount ; one – British Museum (Nat. His.) 1955, 277 (1) – in a depth of 860 fm. from a position 162° , 11,740 yards from the beacon, and the other – British Museum (Nat. His.) 1955, 277 (2) – in a depth of 1,500 fm. from a position 022° , 9,400 yards from the beacon. Both samples contained species of planktonic foraminifera characteristic of warm water. No attempt was made to detach samples of solid rock from this feature. A good place to collect such samples would be from the steep northwesterly slopes. These steep slopes are similar to those found on terrestrial basaltic cones, and steeper than those on more acid extrusives. This would suggest that the tablemount is a basaltic mass. It is, therefore, likely that this tablemount is the remains of a basaltic mountain which millions of years ago projected above sea-level, the top being denuded by wave action, as suggested by CAROLA and DIETZ (1952) for two Pacific tablemounts. The volcanic mass may have sunk gradually to its present depth because of the excess weight on the sea floor. Although more detailed investigations are required to test this hypothesis, it is interesting to recall that one of the first submarine features where it was possible to assign an age and origin was Providence Reef, 220 miles north-north-east of Cape Amber, Madagascar. On the basis of a rock specimen dredged from a depth of 744 fm. it was possible to assign an Eocene-Oligocene age to the vulcanism (WISEMAN, 1936).

The second feature was surveyed by dead-reckoning from an astronomical fix. The reason for this was that a radar-reflecting beacon, anchored in 950 fm., failed to withstand the effects of a northeasterly gale. From a later fix on the beacon anchored on Andrew Tablemount it was calculated that the average set during this survey was 0.56 knots in a 263° direction. This correction was, therefore, applied to the dead reckoning track. Soundings, carried out over a period of 17 hours, revealed an elongated feature some 12 miles long and 4 miles wide, with a least depth of 935 fm. in $06^{\circ} 23.5'N$, $50^{\circ} 14.75'E$ (Fig. 5). It has a relatively flat top which has an easterly tilt as shown in profile *G-H* of Fig. 6. There is a comparatively steep slope on its southwestern side, but on the northeastern side the slope is gentler. Depths of up to 1,400 fm. occur between this feature and Andrew Tablemount. Unfortunately the survey was not extended to the northwest and southeast, so in these directions the depths at its base are unknown. There is, however, to the southeast, an isolated sounding of 1,690 fm. (Fig. 2). It would, therefore, seem likely that the top of this feature is not, on all sides, 3,000 ft. above its base, and it is consequently classed as a seaknoll. It is proposed that this feature should again be named after the navigating officer, Lt. Cdr. A. C. F. DAVID, R.N., and called David Seaknoll ; a name which has the concurrence of the British National Committee on the Nomenclature of Ocean Bottom Features.

In accepting the proposed names, the British Committee appreciates that in the course of time further surveys may well reveal that the two features are minor

protuberances of a much more extensive topographical system, a possibility evident enough from a close study of the adjacent soundings.

British Museum (Natural History), London.

Hydrographic Department, Admiralty, London.

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REFERENCES

- CARSOLA, A. J. and DIETZ, R. S. (1952), Submarine geology of two flat-topped northeast Pacific Seamounts. *Amer. J. Sci.*, **250**, 481-497.
- MATTHEWS, D. J. (1939), *Tables of velocity of sound in pure water and sea water for use in echo-sounding and sound-ranging*. H. D. No. 282, H.M. Stationery Office, London.
- WISEMAN, J. D. H. (1936), The petrology and significance of a rock dredged from a depth of 744 fathoms, near to Providence Reef, Indian Ocean. *Trans. Linn. Soc. Lon., Zool.*, 2nd Ser., **19**, 437-443.
- WISEMAN, J. D. H. and OVEY, C. D. (1953), Definitions of Features on the deep-sea floor. *Deep-Sea Res.*, **1**, 11-16.
- WISEMAN, J. D. H. and OVEY, C. D. (1955), Proposed names of features on the deep-sea floor, 2. General principles governing the allocation of names. *Deep-Sea Res.*, **2**, 261-263.

Suspended echo-sounder and camera studies of midwater sound scatterers

HENRY R. JOHNSON, RICHARD H. BACKUS, J. B. HERSEY and DAVID M. OWEN

Abstract—Twelve-kilocycle-per-second echo sounders have been lowered in the sea to observe sound scatterers at short range. Once, an echo sounder was lowered to a point midway between the surface and a deep scattering layer to record the latter during its evening ascent. Individual scatterers moved upward at a rate of about 15 feet per minute. It was estimated that there was about one scatterer for each 650 m³ of water at the time of the layer's passage by the transducer.

On another occasion a transducer was lowered at night by 35-fathom increments to a depth of about 400 fathoms. Counts of strong scatterers at the several levels were made save in the uppermost where scattering was too intense. Water volume per scatterer varied from about 800 to 2,000 m³ depending on the depth of the observation.

A camera has also been used with the echo sounder to obtain simultaneous acoustic and photographic records of scatterers. The most successful experiments show a correlation between pictures of fishes and strong echoes.

INTRODUCTION

SINCE the discovery of deep scattering layers (DUVALL and CHRISTENSEN, 1946; EYRING, CHRISTENSEN and RAITT, 1948; RAITT, 1948) most observations of these layers have been made with single-frequency echo sounders operating from the surface (HERSEY and MOORE, 1948; DIETZ, 1948; MOORE, 1950; BODEN, 1950; BURD and LEE, 1951; HERDMAN, 1953; and others). If a broad-spectrum sound source is used, several layers may be detected in one locality, each layer having a different peak scattering frequency (HERSEY, JOHNSON and DAVIS, 1952). Furthermore, as some layers migrate in depth there is a gradual shift in their peak scattering frequency (HERSEY and BACKUS, 1954). This is interpreted as meaning that the scatterers change in size (resonant frequency) with changing depth (pressure) such as might be expected if the scatterers were the swimbladders of fishes. This observation supports the contention that bathypelagic fishes are the chief cause of deep scattering layers (MARSHALL, 1951). Furthermore, TUCKER (1951) has shown that there is a correlation between deeper, more intense scattering (at a single frequency), and the vertical distribution of fishes; and shallower, less intense scattering, and the distribution of euphausiids. BURD and LEE (1951) thought that some shallow scattering layers were caused by larval fishes. Arguments have also been advanced for euphausiids (MOORE, 1950 and BODEN, 1950) and squid (LYMAN, 1948) as the chief cause of the sound scattering.

Although the scattering layers on most echo-sounder recordings appear to have the character of reverberation (i.e., many unresolved echoes) rather than resolved, discrete echoes, there has long been unpublished evidence that this is not always the case. Some examples of the latter sort, made from a drifting vessel, were shown to HERSEY by R. S. DIETZ in 1950. Perhaps there are earlier examples of which we are unaware. KANWISHER and VOLKMANN (1955) demonstrated, with a cable-suspended transducer permitting short-range observation, that somewhat deeper scatterers could also be resolved. ANDERSON (1953) made essentially similar observa-

tions but by a very different technique. The present authors have suspended transducers to about 400 fathoms and more recently have used a camera with transducers to make simultaneous acoustic and photographic records of individual scatterers.

SUSPENDED ECHO-SOUNDER EXPERIMENTS

A UQN/1B Edo echo-sounder transducer was lowered in deep water north of Puerto Rico to study the vertical migration of a deep scattering layer at short range. A modified Bludworth recorder was used with the Edo transmitter and receiver. The system had a repetition rate of about 10 pings per second and a ping length of about two milliseconds. The transducer was lowered before sunset to 105 fathoms, the point of minimum sound scattering between the layer and the surface. The instrument was operated continuously until after the postsunset ascent of the layer (Fig. 1). The density of echo sequences† is low in this record until about 15 minutes after sunset (i.e., at 1845) when the scattering layer approached and moved upward past the transducer. At this time the population in the insonified‡ zone was much increased. The layer had moved past the transducer by about 1920 after which time there were markedly fewer echo sequences.

The upward progress of individual animals is recorded, it is believed, for the first time, previous observations having shown the vertical movement of the layer as a whole. The rate of ascent for these individuals was about 30 feet per minute as computed from the indicated change in depth with time on the record (Fig. 1). However, since the scatterers do not swim vertically up the axis of the sound cone nor even swim along paths that pass through the axis of the cone this method of computing the rate of ascent is incorrect. If it is assumed that the scatterers swim up along paths randomly distributed through the sound cone, a rate of ascent of about 15 feet per minute is obtained. This is in general agreement with the rate of ascent for layers as a whole as measured by surface echo sounders (JOHNSON, 1948, and DIETZ, 1948, as well as measurements of our own).

If the record (Fig. 1) is examined for echoes resulting from a single ping, during the maximum of the migration, about 20 discrete echoes may be counted. We assume here that each echo (and echo sequence) came from a single animal*. Furthermore the volume of water insonified by each ping in this record (Fig. 1) was about $45 \times 10^4 \text{ ft}^3$ ($13,000 \text{ m}^3$). Thus there was a single scatterer for about each $2.3 \times 10^4 \text{ ft}^3$ (650 m^3) of water. This may not represent the true population density within this scattering layer when at its midday depth, since there may be an expansion or compression of the layer during its ascent.

Essentially the same gear was used off the continental slope south of New England to test its usefulness in studying vertical distribution of scatterers at short range throughout a greater depth range. A brass ball 6-17 cm in diameter and of known

†An echo sequence is the record of successive echoes from successive pings on a particular scatterer or small group of scatterers.

‡The useful verb to insonify, meaning to fill with sound, does not appear in the standard dictionaries, but is commonly employed in underwater acoustics. For another example of its use see MACHLUP and HERSEY (1955).

*We suppose an echo sequence coming from several animals to be characterized by an interference pattern of intense and faint bands of recording caused by the varying phase relationships as several echoes are received simultaneously at the transducer. There are few echo sequences of this sort on the present record, but see Figs. 4 and 6.

target strength (-38 db at 12 kc ; see SMITH, 1951) was used as a calibration device throughout the experiment. It was suspended 15 fathoms below the transducer on a fine nylon line. At each stage of the lowering, oscilloscope photographs of sound scattering were made, including that scattered by the ball. Thus target strengths of scatterers can be computed by comparison with the ball. A sequence of records was made during hours of darkness down to more than 400 fathoms by 35 fathom increments (Fig. 2)†. Many of the scatterers were comparable in target strength to the ball and a few showed a target strength greater than the ball‡. There is an apparent decrease in the number of scatterers with increasing depth (Fig. 2) with the great concentration of weak scatterers in the upper 35 fathoms being particularly noticeable. Echo sequences from individual strong scatterers are difficult to detect there.

The distribution of scatterers as a function of depth cannot be read directly from Fig. 2 because of the decrease in ship's drift with increasing transducer depth*. This lessens the volume of water scanned per unit of time. The following assumptions were made in determining the rate of drift at various depths : (1) that the transducer was towed at 1 knot at the 34- to 69-fathom depth range and (2) that the movement of the scatterers was small compared with that of the ship during the period of observation. The average duration of echo sequences at the 34- to 69-fathom range was measured and made unity. To compute the rate of drift at the greater depths, the duration of echo sequences at these depths was measured and compared with that observed at the 34- to 69-fathom range. To determine the water volume scanned between 5 and 17.5 fathoms from the transducer during an 11-minute period, a transducer beam width of 30° was assumed. This volume was computed to be

Table 1. *Volume of water per strong sound scatterer at night in the deep ocean off southern New England.*

Depth fathoms	No. of scatterers observed during 11-minute period	Drift knots	Vol. of water scanned, cubic feet	Vol. cubic feet per scatterer	Vol. cubic metres per scatterer
39-51.5	100	1.0	3×10^6	3×10^4	850
68-80.5	28	.5	1.5×10^6	5.3×10^4	1500
107-119.5	16	.33	1×10^6	6.4×10^4	1800
139-151.5	12	.25	$.75 \times 10^6$	6.4×10^4	1800
178-190.5	10	.25	$.75 \times 10^6$	7.5×10^4	2100
212-224.5	21	.20	$.60 \times 10^6$	2.9×10^4	820
250-262.5	9	.12	$.375 \times 10^6$	4.2×10^4	1200
285-297.5	9	.11	$.333 \times 10^6$	3.7×10^4	1050

†Because of failure of the gear this could not be repeated during daylight hours when maxima and minima in the vertical distribution would have been more pronounced. Failure was due to flooding of the electrical cable and the transducer through small cuts caused by the winding of the cable around the wire rope on which the gear was lowered. The winding was due to the torque of the wire rope as it was unrolled from the winch. This difficulty has since been overcome by the addition of an orienting fin which is effective providing the ship has sufficient drift.

‡In examining these data it was noticed that there is a systematic decrease in the sensitivity of the system as a function of increasing depth. This is not understood, but may have been due to slow flooding of the gear or possibly a change in the impedance of the transducer with increasing hydrostatic pressure.

*This is due to the increased sea-anchoring effect as more cable is paid into the water. Minor effects on the accuracy of the count are the loss of sensitivity of the system with increasing depth and receiver gain changes made during the experiment. These factors are not recoverable and are felt to be unimportant if the count of scatterers is made rather close to the transducer.

ECHO SOUNDER RECORD OF ASCENDING SCATTERING LAYER MADE FROM
TRANSDUCER 105 FATHOMS BELOW SURFACE NORTH OF PUERTO RICO

(19° 08' N, 66° 13' W)

26 FEB. 1954

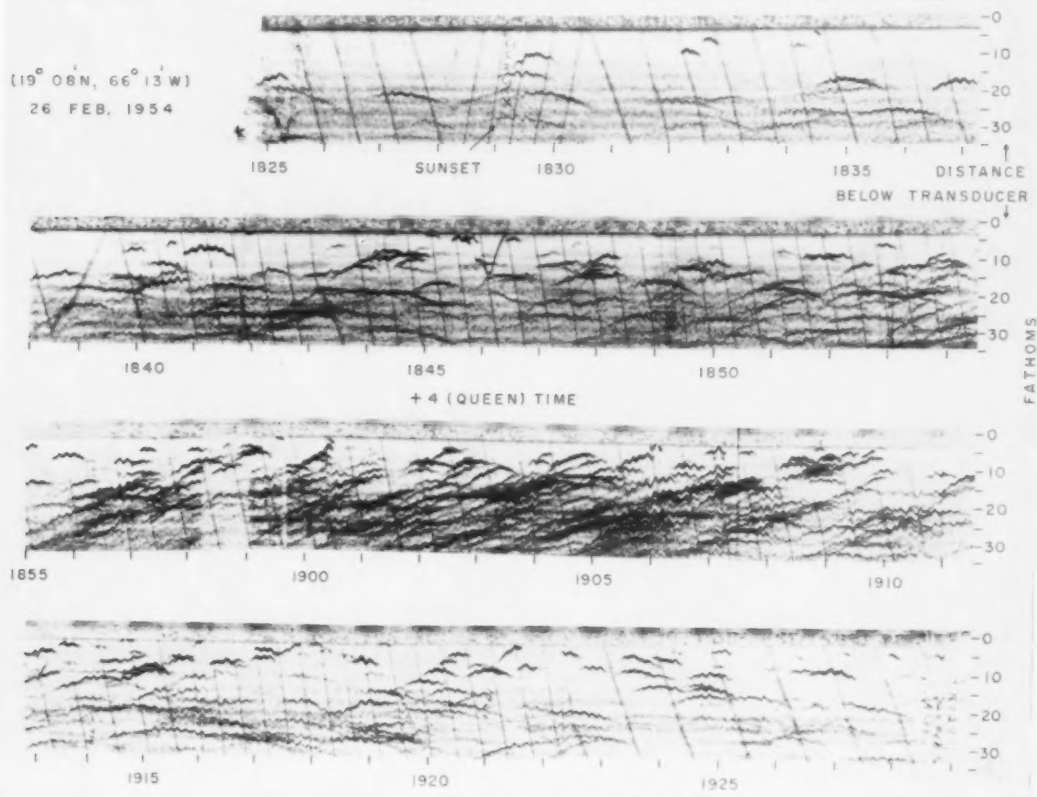


Fig. 1. Suspended echo-sounder record of scattering layer ascent. The roll of the vessel is apparent from the sinuous shapes of the echo sequences as the scatterer's distance from the transducer is alternately increased and decreased. The diagonal traces across the record are time marks from a break-circuit chronometer. Their changes in slope reflect fluctuations in power-line frequency.

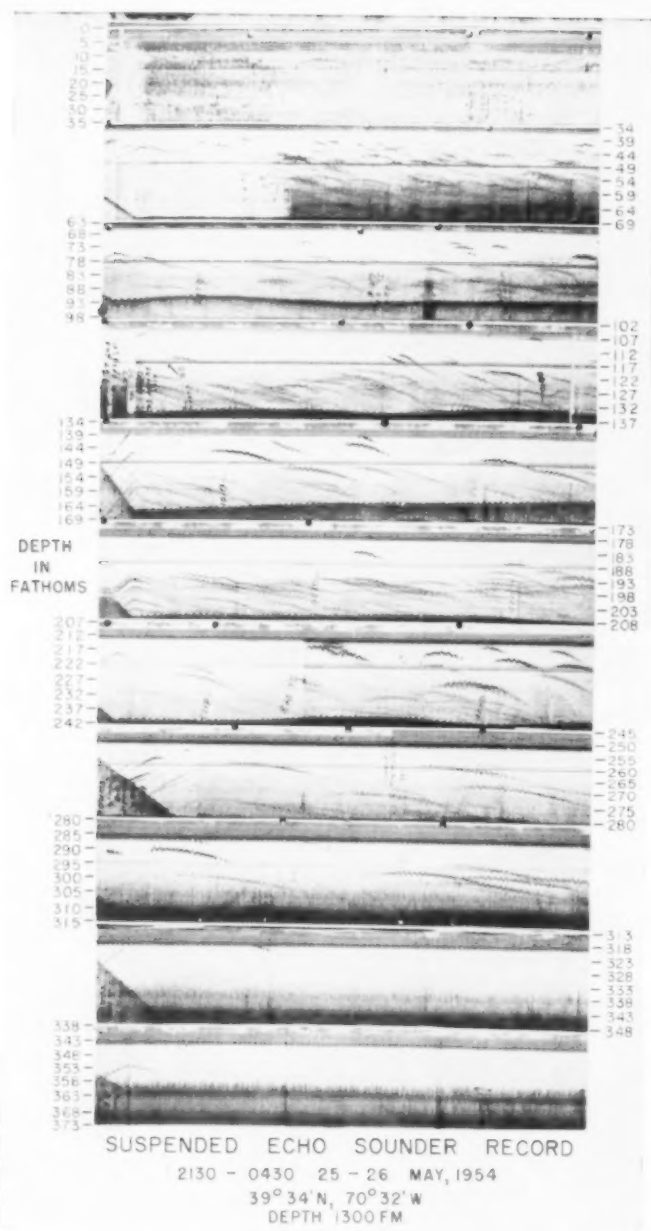


Fig. 2. Echo-sounder record made by lowering transducer by 35-fathom increments (the width of the echo-sounder record). The downward slant from left to right of the echo sequences is due to the cant of the transducer as it is being towed by the drifting ship. The increasing time during which individual scatterers remain in the sound field as the depth of the gear is increased is probably due to the reduction of the speed of the ship's drift as more cable is paid into the water. The continuous constant-depth stripe along the record about 15 fathoms from the transducer is the echo sequence from the brass calibration ball. The solid dark zone of scattering with a sinuous upper margin towards the bottom of each section of the record represents scattering from the sea surface via the back lobe of the transducer. Because of this the depth to the gear could be computed.



Fig. 3. The most recent echo sounder-camera apparatus. Left to right on the iron frame are the electronic flash, Edo transducer (transmit), camera, and QBG transducer (receive). The orienting fin is to the left. The suspension bridle allows either vertically or obliquely downward orientation of the camera and echo sounder. It has been mostly used in the former position since this allows the calibration ball to be suspended on the axis of the acoustic field; however, this is disadvantageous in that the camera photographs the backs of fishes etc., making precise identification difficult.

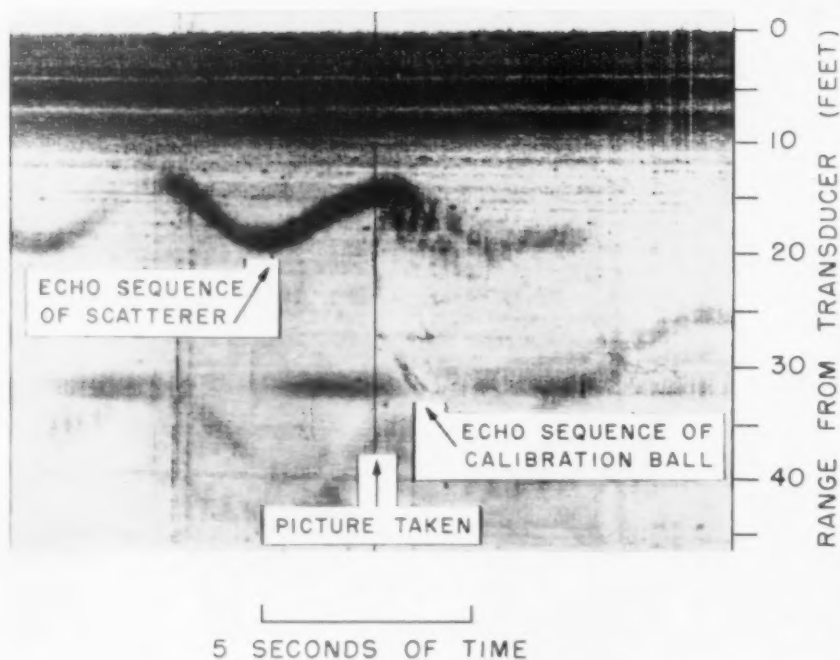


Fig. 4. Photograph and simultaneous acoustic record of 8 unidentified fish made at a depth of 30 metres on 27 February, 1955 at 12° 05' N, 60° 25' W in a water depth of about 1,000 fm. The echosounder record shows the scatterer (in this case a school) at a range of 12.5 feet. The 50-mm-focal-length lens was focused for a distance of 8 feet in water (depth of focus from about 7 feet to 9 feet at $f/6.3$, the iris opening used); thus this picture is somewhat out of focus. By computing the length of the field of the photograph at the 12.5-foot range and multiplying by the proportionate length of the image of the fish we estimate the fish to be about seven inches long.

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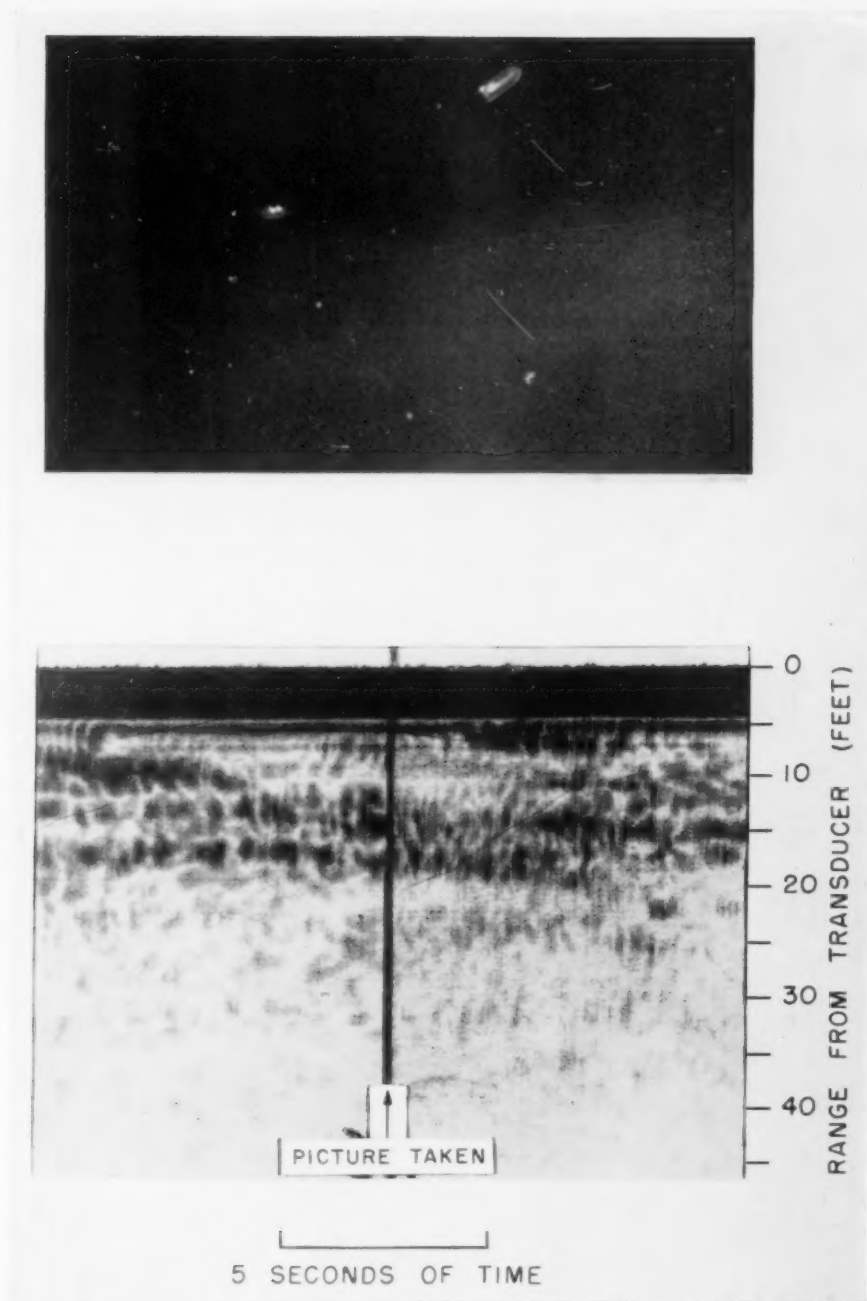


Fig. 5. Salps are seen in a photograph from a lowering made at a depth of 30 metres on 21 July, 1955 at 38° 20' N, 69° 05' W in a water depth of about 2000 fm. The associated acoustic record shows no well-resolved echo sequences within camera range at the time the picture was taken.

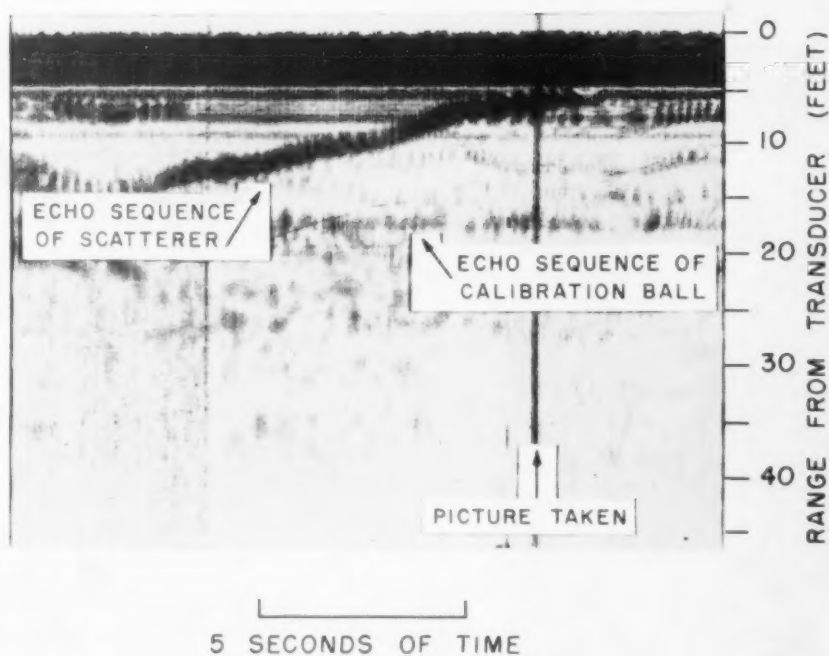


Fig. 6. This couplet was chosen from the same lowering as that in Fig. 5. The fish in the photograph is *Neolotus tripes* Johnson, a trichiurid fish related to the snake mackerel. The associated acoustic record shows a strong echo sequence. The 35-mm-focal-length lens was focused for a distance of six feet in water (depth of focus from about five feet to eight feet at $f/6.3$). The echo-sounder record shows the fish to have been about five and one half feet from the camera. If the proportionate length of the image of the fish is multiplied by the length of the field of the frame for this range the length of the fish would be about six inches (150 mm).



Fig. 7. *Nealotus tripes* Johnson. Length about five and one-half inches (140 mm). The same species as that in Fig. 6. One of about 15 specimens dipnetted at the surface on the evening on which the records in Fig. 6 were made and on the preceding evening. According to MATSUBARA and IWAH (1952), only eight specimens of this widely distributed fish have been previously recorded.

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3×10^6 cubic feet at 1 knot (39-51.5 fathom range), and volumes scanned at other depths were reduced in accordance with the reduced rate of drift.

The number of scatterers in the region from 5 to 17.5 fathoms from the transducer was counted during an 11-minute period for each depth range observed.

The water volumes per scatterer at various depths thus computed are summarized in Table 1, which shows a decrease in population density with increasing depth down to the 212-224.5 fathom depth range where there is a sharp increase in population. This increase actually begins at about 193 fathoms (Fig. 2) but as no count was made of scatterers from 190.5 to 212 fathoms this is not recorded in Table 1. Since a prominent scattering layer is observed in this locality in the daytime at approximately 200 fathoms, it appears that some of the scatterers in it do not migrate.

SUSPENDED ECHO SOUNDER - CAMERA EXPERIMENTS

A camera was added to the suspended echo-sounder system to make simultaneous photographic and acoustic records of sound scatterers (Fig. 3). The intent was to design the system so that a scatterer appearing at a certain range on the echo-sounder record would also be within the purview of the camera and in focus; at this point the camera could be triggered by the echo-sounder operator. A 35-mm Edgerton repeating-flash shutterless deep-sea camera (EDGERTON and HOADLEY, 1955) was used. It could only be operated where an electronic flash was the sole source of light.

Two schemes of lighting have been used. At first, it was thought necessary to use side lighting to reduce the amount of extraneous light reflected to the camera by particulate matter in the water. However, it was found that this reflection was negligible in the clear water of the high seas. Direct lighting does not have the disadvantage of side lighting, which causes the eclipse of one side of the scatterer, making identification difficult. An orienting fin was attached to the rig to prevent the winding of the electrical cable around the wire suspension rope.

The first cruise with this gear indicated that the minimum distance at which the echo sounder could operate was too great to give large enough images in the photographs. This was due to paralysis of the receiving system for a period of several milliseconds after the emission of each ping. To remedy this situation an independent receiving transducer (QBG) was installed. The receiving transducer was fed to the driving amplifier of a high-resolution travel-time recorder. This change made it possible to record echoes from scatterers at ranges as short as five feet†.

Two major deficiencies have controlled the experiments that we have performed with this gear. It was soon apparent that, contrary to expectations, the acoustic field of the echo-sounder system was much larger than the optical field of the camera. From a series of rough measurements we have seen that good echoes can be obtained throughout a field having an angle at the apex of about 90° . The camera lenses used have angles of $20^\circ \times 30^\circ$ (50 mm focal length) or $30^\circ \times 40^\circ$ (35 mm focal length) in water. The discrepancy is in fair agreement with the average percentage of "misses" (40%) obtained in the photographs when strong scatterers are indicated on the acoustic record. An acoustic system with greater directionality appears to be a logical improvement.

†At such short ranges the driver amplifier must be operated at low gain which results in inability to record scatterers except at rather short range.

Secondly, the observed decrease in sensitivity of the acoustic system with increasing hydrostatic pressure has limited our observations of deep scattering layers to hours of darkness when the layers are near the surface. This has the obvious disadvantage of having nonmigrating, near-surface scatterers mixed in with the population in which we are particularly interested.

About 40% of the photographs accompanying strong echo sequences show nothing. It is unlikely that the sound scatterers in such cases are too small or too transparent to be revealed on the film, but that they lie outside the purview of the camera. Until this technical difficulty is overcome various objects cannot be associated with a certain echo quality. On the contrary, given an object, its echo can be loosely described. The data in Table 2 summarize the results of a lowering made on 21 July, 1955. In describing this lowering we do not imply that this experiment is representative of our experience so far. In a half-dozen earlier lowerings in which reasonable success might have been expected, only images of blobs were found in the photographs. In these earlier experiments we mostly operated at a much higher recorder amplifier gain which probably accentuated the disparity between the acoustic and optical fields as well as decreased our ability to distinguish between echoes of different amplitudes on the echo-sounder record.

The photographs made during the 21 July lowering have been classified as blank, blobs, unidentified objects, salps, and fishes (Table 2). The echoes recorded at the time of the photographic exposures have been classified as poor, 20%; and as good, 63% of the total. 16% of the time no echoes were recorded[‡]. If there is no correlation between a class of object and the quality of its echo, each class of object photographed should be accompanied by echoes of the three kinds in the same proportion as they occur in the total. Departures from the expected percentages

Table 2. Summary of the results of an echo sounder-camera lowering.

Picture	Echo sequence								
	None			Poor			Good		
	No.	Expected	Observed	No.	Expected	Observed	No.	Expected	Observed
Blank	2	16%	40%*	1	20%	20%	2	63%	40%*
Blobs†	4	16%	14%	9	20%	31%	16	63%	55%
Unident. irregular objects	2	16%	14%	4	20%	28%	8	63%	58%
Salps	8	16%	18%	9	20%	20%	28	63%	62%
Fishes	0	16%	0%*	0	20%	0%*	18	63%	100%*

[‡]In thus "classifying" echoes we have in mind only qualitative judgements about the amplitude and general clarity (signal-to-noise ratio) of the individual echoes. With the possible exception of recognizing multiple scatterers from interference patterns in an echo sequence we do not regard descriptions of echo "quality" of further use in identifying scatterers.

*See text.

†All picture classes are self-explanatory save blobs. The latter images have appeared in all of our lowerings. These are round images, small when in focus and larger when out of focus. Often, when they occur along the edges of our pictures they are somewhat elongated and are so oriented as to point towards the centre of the frame (Fig. 4). These, then, are the so-called coma, originating from objects acting as point sources of light when seen by uncorrected lenses. They are familiar in astronomical photography. In the present case we presume them to be caused by particulate matter of a small size. However, in the case of large blobs, larger, out-of-focus objects could be the source of these images.

indicate a correlation between class of object and echo category. The departures in Table 2 that are deemed possibly significant are few and are marked with an asterisk. In the case of pictures showing nothing there are more such pictures than expected when there is no echo and fewer than expected when there is a good echo. If, with such a small sample, anything is indicated it is that a correlation exists between some of the remaining classes of objects and the category of the echo. With respect to blobs, unidentified objects, and salps, the observed percentages are close to the expected percentages for all echo categories indicating no correlation for these object classes. For fishes, however, the observed values are very different from the expected values. There are no pictures of fishes accompanied by no echo or poor echoes; rather, all pictures of fishes are accompanied by strong echoes. Thus this experiment adds to earlier evidence that fishes are important sources of strong deep-ocean sound scattering.

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REFERENCES

- ANDERSON, V. C. (1953), Wide band sound scattering in the deep scattering layer. *SIO Ref.* 53-36, 1-35. (Unpublished manuscript).
- BODEN, B. P. (1950), Plankton organisms in the deep scattering layer. *Rept. U.S. Navy Electronics Laboratory* 186, 1-29. (Unpublished manuscript).
- BURD, A. C. and LEE, A. J. (1951), The sonic scattering layer in the sea. *Nature*, **167** (4251), 624.
- DIETZ, R. S. (1948), Deep scattering layer in the Pacific and Antarctic Oceans. *J. Mar. Res.* **7** (3), 430-442.
- DUVALL, C. E. and CHRISTENSEN, R. J. (1946), Stratification of sound scatterers in the ocean. *J. Acous. Soc. Amer.* **18** (1), 254.
- EDGERTON, H. E. and HOADLEY, L. D. (1955), Cameras and lights for underwater use. *J. Mot. Pict. Tel. Eng.* **64**, 345-350.
- EYRING, C. F., CHRISTENSEN, R. J. and RAITT, R. W. (1948), Reverberation in the sea. *J. Acous. Soc. Amer.* **20** (4), 462-475.
- HERDMAN, H. F. P. (1953), The deep scattering layer in the sea: Association with density layering. *Nature* **172** (4372), 275-276.
- HERSEY, J. B. and BACKUS, R. H. (1954), New evidence that migrating gas bubbles, probably the swimbladders of fish, are largely responsible for scattering layers on the continental rise south of New England. *Deep-Sea Res.* **1** (3), 190-191.
- HERSEY, J. B., JOHNSON, H. R. and DAVIS, L. C. (1952), Recent findings about the deep scattering layer. *J. Mar. Res.* **11** (1), 1-9.
- HERSEY, J. B. and MOORE, H. B. (1948), Progress report on scattering layer observations in the Atlantic Ocean. *Trans. Amer. Geophys. Un.* **29**, 341-354.
- JOHNSON, M. W. (1948), Sound as a tool in marine ecology, from data on biological noises and the deep scattering layer. *J. Mar. Res.* **7** (3), 443-458.

- KANWISHER, J. and VOLKMANN, G. (1955), A scattering layer observation. *Science* **121** (3134), 108-109.
- LYMAN, J. (1948), The sea's phantom bottom. *Sci. Month.* **66** (1), 87-88.
- MACHLUP, S. and HERSEY, J. B. (1955), Sound-scattering observations of scatterers in the ocean. *Deep-Sea Res.* **3**, 4, par. 1, line 7.
- MARSHALL, N. B. (1951), Bathypelagic fishes as sound scatterers in the ocean. *J. Mar. Res.* **10**, 1-17.
- MATSUBARA, K. and IWAI, T. (1952), Studies on some Japanese fishes of the family Gempylidae. *Pacif. Sci.* **6**, 193-212.
- MOORE, H. B. (1950), The relation between the scattering layer and the Euphausiacea. *Biol. Bull.* **99** (2), 181-212.
- RAITT, R. W. (1948), Sound scatterers in the sea. *J. Mar. Res.* **7** (3) 393-409.
- SMITH, P. F. (1954), Further measurements of the sound scattering properties of several marine organisms. *Deep-Sea Res.* **2**, 71-79.
- TUCKER, G. H. (1951), Relation of fishes and other organisms to the scattering of underwater sound. *J. Mar. Res.* **10** (2), 215-238.

On the determination of the depth of no meridional motion

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Abstract—The depth of no meridional geostrophic velocity is determined from a pair of hydrographic stations in the Sargasso Sea, on the premise that the deep flow is frictionless. Certain implications regarding the eddy and advective flux of heat in the deep water are also discussed.

WE WILL consider the consequences of EKMAN's classical concept of dividing the central ocean circulation into a shallow wind-driven surface layer of frictional influence, and a deeper frictionless geostrophic flow, when it is applied to actual hydrographic data, rather than to an abstract homogeneous ocean. We proceed to define a rectangular co-ordinate system, with origin at the sea surface, with x directed eastward, y northward, z upward, and u , v , and w representing the corresponding velocity components. The Coriolis parameter is f . Denote pressure by p , density by ρ , the x and y components of shearing stresses across horizontal planes by τ_x and τ_y , and the acceleration due to gravity by g . In central oceanic regions we assume that the hydrographic-station data are representative of a time-averaged steady density field, and we assert that the inertial terms are negligible. The system is then described by the following equations

$$-f\rho v = -\frac{\partial p}{\partial x} + \frac{\partial \tau_x}{\partial z} \quad (1)$$

$$f\rho u = -\frac{\partial p}{\partial y} + \frac{\partial \tau_y}{\partial z} \quad (2)$$

$$g\rho = -\frac{\partial p}{\partial z} \quad (3)$$

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0 \quad (4)$$

Elimination of pressure by cross-differentiation leads to the following three relations

$$\frac{\partial}{\partial z}(\rho v) = -\frac{g}{f} \frac{\partial \rho}{\partial x} - \frac{1}{f} \frac{\partial^2 \tau_x}{\partial z^2} \quad (5)$$

$$-\frac{\partial}{\partial z}(\rho u) = -\frac{g}{f} \frac{\partial \rho}{\partial y} - \frac{1}{f} \frac{\partial^2 \tau_y}{\partial z^2} \quad (6)$$

$$\frac{\partial}{\partial z}(\rho w) = \frac{\beta}{f} \rho v - \frac{1}{f} \frac{\partial}{\partial z} \left[\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \right] \quad (7)$$

where $\beta = \partial f / \partial y$.

The quantity ρv can be eliminated between equations (5) and (7).

$$\frac{d^2 \rho w}{dz^2} = -\frac{\beta g}{f^2} \frac{\partial \rho}{\partial x} - \frac{d^2}{dx^2} F(z) \quad (8)$$

where

$$F(z) \equiv \frac{\partial}{\partial x} \left(\frac{\tau_y}{f} \right) - \frac{\partial}{\partial y} \left(\frac{\tau_x}{f} \right).$$

Equation (8) is written as a total differential equation because $\partial\rho/\partial x$ is known (from a pair of hydrographic stations both on the same latitude circle) along a vertical as a function of z , and $F(z)$ is to be regarded as a more or less undeterminable function of z , into whose detailed structure we will not inquire, but merely suppose that, following EKMAN, it differs from zero only in a thin upper layer extending from $z = 0$ to $z = -D$, the depth of frictional influence. The value of $F(0)$ is known explicitly in terms of the distribution of wind stress on the sea surface in the neighbourhood of the pair of hydrographic stations. The ocean bottom is at $z = -B$. A first integral of equation (8) can now be obtained.

$$\frac{d}{dz} \rho w = \frac{\beta}{f} [\phi(z) + C] - \frac{dF}{dz} \Big|_{-B}^z \quad (9)$$

where we define

$$\phi(z) \equiv -\frac{g}{f} \int_{-B}^z \frac{\partial \rho}{\partial x} dz$$

and C is a constant of integration. The meaning of the function $\phi(z)$ is familiar, because for purely geostrophic flow (from equation 5) we have simply

$$\rho v = \phi(z) + C$$

and the constant C is the undetermined reference velocity. This amounts, of course, to the traditional method of *dynamic computation* and the undetermined constant of integration is the undetermined meridional mass flux ρv at the bottom. Thus we see that the determination of C is equivalent to determining the *depth of no motion*, i.e. the depth at which ρv vanishes. We will henceforth avoid both italicized terms because they are misleading; indeed we will find that the level of no meridional motion coincides with the maximum vertical motion, and that the level of no zonal motion does not necessarily coincide with either.

Since in the real ocean time-averaged bottom currents are weak, we may write, by hypothesis, $\frac{dF}{dz} \Big|_{-B}^z = \frac{dF}{dz}$, and equation (9) may be integrated once again between the limits z and $-B$, and taking $F(-B) = 0$, $\rho w(-B) = 0$, the following expression for ρw is obtained.

$$\rho w = \frac{\beta}{f} \left[\int_{-B}^z \phi(z) dz + C(z+B) \right] - F(z) \quad (10)$$

At the surface $z = 0$, ρw vanishes (or is fixed by some small known mean evaporation-precipitation correction). The quantity $F(0)$ is simply the well-known net convergence of the Ekman wind-driven layer as computed for ocean areas (MONTGOMERY, 1936). Thus the constant C is determined by the following relation

$$C = \frac{1}{B} \left[\int_{-B}^0 F(0) - \int_{-B}^0 \phi(z) dz \right] \quad (11)$$

The depth at which $\phi(z) + C$ vanishes is the depth of no meridional motion. The same analysis cannot be applied to determine the zonal component of velocity ρu .

The velocity component ρu is determined, in principle, however, from equation (4), because the fields of ρv and ρw are determined. From a practical point of view a very detailed network of hydrographic stations would be necessary to develop the field of the quantity ρu .

In physical terms the method which we have discussed above in formal terms can be loosely described as follows. At any geographical position in the ocean the distribution of the winds produces a net convergence (or divergence) of surface waters. The only place for this water to escape (or come from) in the steady-state is downward (upward) through the bottom of the surface frictional layer. In the deep frictionless (by hypothesis) geostrophic flow, water elements stretch (or shrink) vertically if they move poleward (equatorward). The cumulative effect of such stretching and shrinking, added up over the entire vertical column from the ocean bottom to the bottom of the frictional layer, leads to a vertical component of velocity which must, by mass conservation, equal that induced at the bottom of the frictional layer by the winds. This matching occurs only for a specific choice of reference level and the latter is thereby determined.

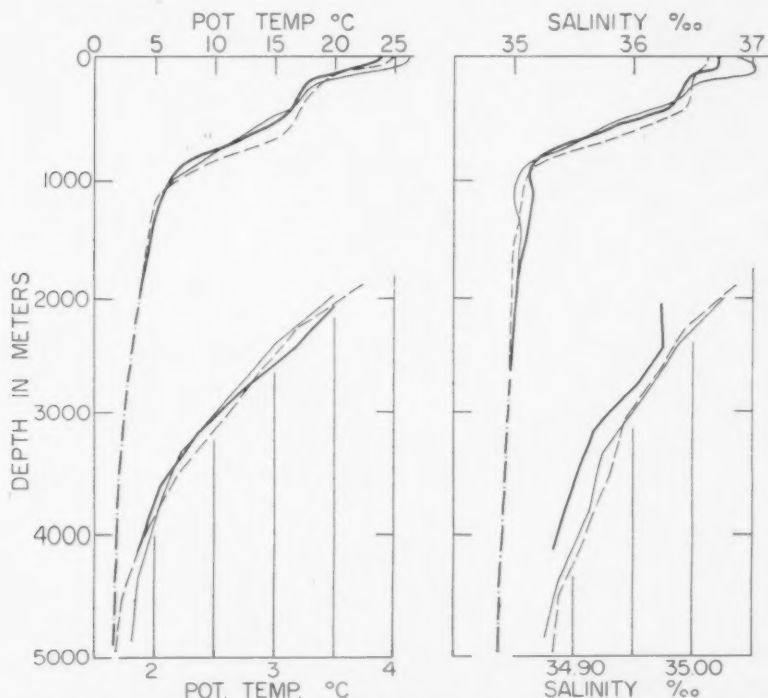


Fig. 1. Potential temperature and salinity at *Atlantis* Stations 5203 (dashed) 5210 (solid) and 5215 (light solid). Below 2,000 metres the abscissae are shown expanded ten times, in order to exhibit detail.

If the hypothetical elements of this analysis obtain in nature, we now have a way of computing the actual vertical profile of meridional velocity – except in the frictional layer itself, where there is some ambiguity due to our lack of knowledge of the distribution of eddy viscosity. We also have computed the actual vertical distribution

of the vertical component of velocity (equation 10). We cannot determine the reference level of the zonal velocity from the data of a pair of hydrographic stations, as computed from equation (6). In principle, however, for an ocean area well covered by hydrographic data, the zonal component of velocity is determined through equation (4) and a coastal boundary condition because the other components are known by the above theory.

In order to illustrate the method and its implications, a numerical example is presented here. Three of WORTHINGTON's recent *Atlantis* stations in the Sargasso Sea are used: 5203, 5210, and 5215. The vertical distribution of potential temperature and salinity is illustrated in Fig. 1.

Table 1. Numerical Examples
Atlantis Stations 5203 32°00'N 63°03'W
 5210 32°00'N 50°41'W

Depth <i>m</i>	Specific Volume Anomaly		$\phi(z)$ cm sec ⁻¹	$\int_{-B}^z \phi(z) dz$ 10 ⁴ cm ² sec ⁻¹	$\rho w + F(z)$ 10 ⁵ cm sec ⁻¹	ρv cm sec ⁻¹
	5203 10 ⁻⁵ cm ³ gm ⁻¹	5210				
0	331.5	298.3	-2.587	-20.58	-9	-2.2
50	265.0	240.0	-2.402	-19.33	-6	-2.1
100	200.0	184.5	-2.263	-18.16	-4	-1.9
150	180.2	173.6	-2.176	-17.06	-1	-1.8
200	176.6	168.6	-2.140	-15.97	+1	-1.8
250	174.0	166.5	-2.095	-14.92	3	-1.7
300	172.3	165.0	-2.053	-13.88	5	-1.7
350	171.4	162.0	-2.013	-12.86	7	-1.7
400	170.8	157.3	-1.960	-11.87	9	-1.6
450	168.6	150.5	-1.885	-10.91	11	-1.5
500	159.5	138.8	-1.784	-9.99	13	-1.5
600	142.8	120.5	-1.553	-8.32	16	-1.2
700	123.8	96.9	-1.305	-6.89	19	-1.0
800	99.9	77.0	-1.005	-5.74	21	-0.7
900	79.7	62.9	-0.749	-4.86	22	-0.4
1000	61.9	54.8	-0.562	-4.21	22	-0.2
1200	51.3	49.0	-0.404	-3.24	23	-0.1
1400	48.5	45.9	-0.352	-2.49	24	-0.02
1600	46.7	44.9	-0.294	-1.84	24	+0.04
1800	46.3	44.4	-0.254	-1.29	23	0.08
2000	46.3	43.6	-0.212	-0.84	23	0.12
2500	44.5	43.9	-0.061	-0.14	20	0.27
3000	43.4	43.5	-0.028	-0.09	17	0.31
3500	43.0	43.4	-0.033	+0.25	13	0.30
4000	43.9	42.8	0.000	+0.33	9	0.34
4500	43.7	44.6	0.061	+0.18	5	0.40
5000			0.011	0.00	0	0.34

Other numerical values used: $f = 0.773 \times 10^{-4} \text{ sec}^{-1}$

$\beta = 1.9 \times 10^{-13} \text{ cm}^{-1} \text{ sec}^{-1}$

$F(0) = -9 \times 10^{-5} \text{ cm sec}^{-1}$ (from MONTGOMERY, 1936)

Distance between stations = $1.16 \times 10^8 \text{ cm}$

Value found: $C = 0.338 \text{ cm sec}^{-1}$

The calculation of the meridional and vertical velocity distributions is carried out in Table 1. The depth of no meridional motion is found to be about 1,500 metres. The maximum value of vertical velocity, $24 \times 10^{-5} \text{ cm/sec}$, is also found at this depth. This is also very nearly the depth of the centre of the high-salinity anomaly water from the Mediterranean.

In order to carry the investigation further, for example into the question of heat fluxes, etc., the reference level for the zonal velocity component is, in general, needed. Since we do not have this information we can only discuss heat fluxes where zonal advection appears to be inconsiderable. For example, in the divergence of heat flux equation (θ denotes temperature)

$$\frac{\partial \theta}{\partial t} + u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} + w \frac{\partial \theta}{\partial z} = K \frac{\partial^2 \theta}{\partial z^2}$$

we are forced to estimate $\partial \theta / \partial t$ and u in the left-hand member. In the water below 1,000 metres (Table 2) it seems probable that the last term of the left-hand member dominates entirely, for any reasonable estimates of the first two terms, and hence must be balanced by the vertical conduction divergence on the right-hand side. In this way we compute the vertical eddy coefficient of thermal conductivity K . Of

Table 2. Evaluation of Terms in the Divergence of Heat Flux Equation

Depth <i>m</i>	* $\frac{\partial \theta}{\partial t}$ 10 ⁻⁸ sec ⁻¹	† $u \frac{\partial \theta}{\partial x}$ 10 ⁻⁸ sec ⁻¹	$v \frac{\partial \theta}{\partial y}$ 10 ⁻⁸ sec ⁻¹	$w \frac{\partial \theta}{\partial z}$ 10 ⁻⁸ sec ⁻¹	$\frac{\partial^2 \theta}{\partial z^2}$ 10 ⁻⁸ cm ⁻²	<i>K</i> cm ² sec ⁻¹
1000	(0.02)	0.25	0.06	1.00	0.10	8
1500	(0.02)	(-0.10)	0.00	0.46	0.06	8
2000	(0.02)	(± 0.05)	< 0.01	0.28	0.02	14
3500	(0.02)	(± 0.05)	0.00	0.13	0.01	13

* Based on estimated maximum probable long-term trend of 0.2°C per 30 years.

† Based on estimated maximum probable value of ρu , ± 0.5 cm sec⁻¹.

course little confidence can be placed in the exact numerical values of K , but the order of magnitude is defensible. A consideration of the salt flux divergence leads to similar values of the eddy diffusivity. Unless the eddy coefficient of viscosity is three or four orders of magnitude greater than K , there is no inconsistency in taking $F(z) = 0$ in the deep water. Finally there are some comments which I would like to make:

(1) The idea that friction is dynamically unimportant in the deep water is purely hypothetical, and will have to be justified eventually by its results.

(2) The concept of a hydrodynamical situation in which mixing is important, but friction unimportant, is an odd one, and deserves further study.

(3) There is nothing in this treatment to imply that the ocean is entirely wind-driven; indeed in another place (STOMMEL, 1956, Chap. xi) I have given reasons for supposing that a large portion of the ocean circulation is thermohaline in origin.

(4) The relatively large values of vertical velocity and diffusivity in the Sargasso Sea indicate that the deep water cannot be much more than 200 years older than the surface water—in contradiction to the tenfold greater age reported by KULP (1953) from carbon-14 measurements.

(5) The depth of no meridional motion in the Sargasso Sea determined by the above method nearly coincides with that inferred by DEFANT (1941) from intuitive considerations. One hopes that eventually there will be a direct observational check.

(6) The notion that there is a level of no motion in the ocean, where all three

velocity components vanish, is not substantiated; indeed maximum upward velocity is found to occur at the depth of no meridional velocity.

(7) The method is not unrelated to SVERDRUP's (1947) vertically integrated transport functions, but differs in that the vertical density structure is considered in detail. Like SVERDRUP's theory, *the method is restricted to central oceanic areas*, well removed from high-velocity boundary currents like the Gulf Stream. Another previous attempt to match the flow from the frictional layer to deeper geostrophic flow is the rather different discussion by MONTGOMERY (1938, pp. 38-40).

(8) A reviewer has recommended that, in order to avoid confusion, I should state explicitly that vertical velocities in the steady state do not necessarily imply mixing. For example, flow along sloping isothermal surfaces, in which the dominant terms in the heat-divergence equation are the last three terms of the left-hand member, does not necessarily do so. Indeed, in the upper layers of the Sargasso Sea this latter condition seems to occur; and it is for this reason that the calculations in Table 2 are limited to 1,000 metres and deeper.

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REFERENCES

- DEFANT, A. (1941), Die absolute Topographie des physikalischen Meeresniveaus und der Druckflächen, sowie die Wasserbewegungen im Atlantischen Ozean. *Deutsche Atlantische Exped. "Meteor" 1925-27, Wiss. Erg.*, **6**, 191-260.
- KULP, J. L. (1953), Climatic change and radioisotope dating, pp. 201-8, in *Climatic change*, edited by A. H. SHAPLEY, Harvard Univ. Press (1953), 318 pp.
- MONTGOMERY, R. B. (1936), On the momentum transfer at the sea surface, III, transport of surface water due to the wind system over the North Atlantic. *Pap. Phys. Oceanogr. Meteorol.*, **4** (3), 23-30.
- MONTGOMERY, R. B. (1938), Circulation in the upper layers of southern North Atlantic deduced with use of isentropic analysis. *Pap. Phys. Oceanogr. Meteorol.*, **6** (2), 1-55.
- STOMMEL, H. (1956), *The Gulf Stream*, Univ. of California Press (in press).
- SVERDRUP, H. U. (1947), Wind-driven Currents in a Baroclinic Ocean; with Application to the Equatorial Currents of the Eastern Pacific. *Pro. Nat. Acad. Sci.*, **33**, 318-326.

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The specific alkalinity

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Abstract—The variations of the specific alkalinity in ocean water are studied on the basis of the measurements carried out in the Atlantic, Indian, and Pacific Ocean during the Swedish Deep-Sea Expedition. Each water mass shows a characteristic specific alkalinity as a result of the circulation and the life processes going on in the ocean. The production of carbonic acid and the lime secretion by organisms seem to be the main factors influencing the alkalinity. The stability of the stratification seems to increase the specific alkalinity together with the content of carbon dioxide in deep waters. Surface waters in the equatorial region show a low specific alkalinity; polar and subpolar waters generally are enriched, as are also deep waters. The specific alkalinity grows with the depletion of oxygen, and is highest in the Pacific and lowest in Atlantic deep waters. The range of variation is within 0.119 and 0.130, with an average of all water masses of about 0.126. The value is about 3 per cent higher than that quoted by WATTENBERG, who had investigated only Atlantic waters, but it is in agreement with all the alkalinity measurements made hitherto.

THE formation of limestone and calcareous sediments covering about 30 per cent of the earth is co-ordinated with the geochemistry of its components, the calcium and the carbon dioxide system, in the ocean. In order to study the organic and inorganic precipitation of lime, as also, on the other hand, its dissolution, WATTENBERG (1933) carried out a comprehensive investigation of the alkalinity and the hydrogen-ion concentration in sea water during the *Meteor* cruise. Recently RUBEY (1951) devoted a very stimulating study to the changes of the system during geological time, and discussed the limits within which the content of carbonates may have varied since the origin of the ocean. Hitherto there existed only the determination by WATTENBERG (1933) in the South Atlantic Ocean. From the Pacific Ocean the determinations on two deep stations are given as graphs in the report of the *Carnegie* cruise by REVELLE (1944). The methods used show considerable divergences and it was therefore uncertain if the results could be compared. All other determinations are made in coastal waters. For that reason, during the Swedish Deep-Sea Expedition, the alkalinity was determined in more than 1,500 samples. The results are published in the Reports of the Swedish Deep-Sea Expedition, where the method also is given.

The alkalinity, defined as the number of milliequivalents of hydrogen-ion neutralized by one litre of sea water at 20°C, was determined by the method of ANDERSSON and ROBINSON (1946) using the principle outlined by THOMPSON *et al.* (1931, 1940). The method consists of the addition of 25 ml 0.015N HCl to 100 ml sea water followed by the determination of the resulting pH. The alkalinity is read from a graph. For more details see the report of the Swedish Deep-Sea Expedition (BRUNEAU, JERLOV and KOCZY, 1953). In order to realize the possibility of comparing the alkalinity from different localities and depths, the specific alkalinity is calculated, which is given by the ratio of alkalinity, as millival. per litre, to chlorinity, as g/kg. This mixed ratio is now generally avoided but was used throughout by WATTENBERG. As long as the samples are of oceanic origin with small variation in chlorinity, the ratio of alkalinity

to chlorinity shows the same constancy as the ratio of alkalinity to chlorosity. The deviation can be at maximum 0.0005, when no attention is given to the samples taken near shore, in the Red Sea and the Mediterranean. For that reason the specific alkalinity is used, which is easily compared with the values given by WATTENBERG for the Atlantic Ocean. The conversion factor giving the alkalinity-chlorosity ratio in for all samples 0.9758 with a standard deviation of 0.0002 which is less than the error attributed to the alkalinity determinations.

The specific alkalinity indicates the changes due to the calcium precipitation or dissolution, but should not be affected by the mixture of water masses with different salinities, if not the history of the water in respect to the geochemistry of calcium carbonate is different. Water masses containing lime secreting organisms should show a low specific alkalinity. The contrary should be the case in bottom water streaming over calcareous sediment where it may be assumed that calcium-carbonate is dissolved. The condition promoting the dissolution and resulting in a high specific alkalinity is an increased carbonate aggressivity of the water, which is dependent on the content of carbonic acid, the temperature, and the depth. With rising pressure of carbon dioxide, increasing depth and decreasing temperature the solubility of carbonates increases. Therefore the specific alkalinity increases with depth in water masses saturated with carbonate. WATTENBERG demonstrated in his classical treatment that an important factor affecting the specific alkalinity is related to the formation and melting of sea ice, as the content of chlorine in sea ice diminishes with time, but not the calcium content. The ratio of calcium to chlorine, therefore, increases in ice, as it was clearly shown by chemical analyses during the *Sjedov* expedition (WIESE, 1930).

By intermixing of water masses, as upwelling and enforced eddy diffusivity, the extreme values of the specific alkalinity which is created by the factors given above, are counterbalanced. A state of equilibrium may result with an intermediate specific alkalinity.

By evaporation of water vapour, as also by dilution with rainwater, the specific alkalinity is not changed. On the other hand, however, the possibility that by the addition of "excess" volatiles the specific alkalinity can be changed must be considered. It seems most likely that the specific alkalinity is in that case reduced and the chlorinity increased, but that may vary within wide limits, from region to region, with the composition of the volatiles.

THE VARIATION WITH SALINITY

In the calculation of the specific alkalinity the relative variation becomes less than the total alkalinity. In Fig. 1 are both the total alkalinity and the specific alkalinity values given for the east Pacific Ocean. Whereas the alkalinity varies between 2.1 and 2.5 millival/l, the specific alkalinity varies between 0.113 and 0.130. The effect of evaporation disappears as both chlorinity and alkalinity are increased by the same amount. About the same pattern of the $Cl-A/Cl$ relation is found in all oceans investigated by the Swedish Deep-Sea Expedition. But it must be pointed out that the samples are taken in the equatorial regions except in the Atlantic where also samples to 43°N were taken.

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The general trend of the relation of specific alkalinity to salinity is that the salinity varies in wide limits for low specific alkalinity but shows a constant value for high specific alkalinity values. The cause is found in the variation of salinity with depth.

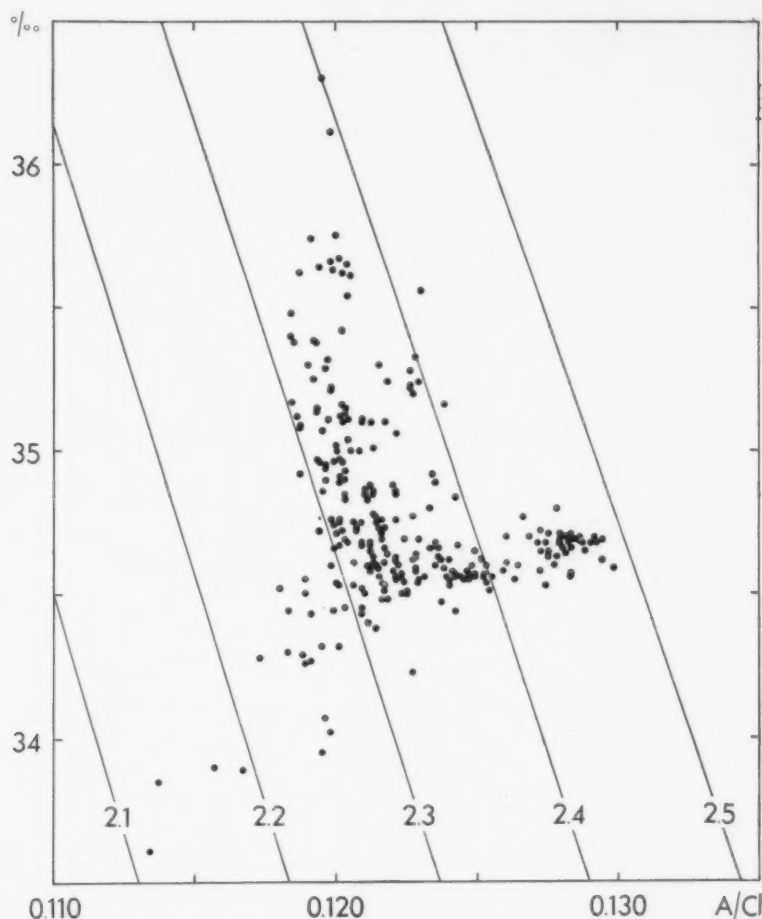


Fig. 1. The relationship between salinity and specific alkalinity in the central and western Pacific Ocean. The lines in the figure denote the values of the alkalinity in milliequivalents.

VARIATIONS WITH DEPTH

The values in surface waters in the Pacific and Indian Ocean are scattered around an average of 0.120. The average in the Atlantic Ocean is 0.122. The specific alkalinity decreased toward 25 and sometimes 50 m. Here the optimal conditions for lime secreting organisms seem to exist, but exceptions to this rule were also found. In intermediate waters the specific alkalinity increases. The gradient of the increase changes from region to region, as also the values vary within wide limits.

The deep waters seem to represent the most thoroughly mixed water masses, as the deviation of the values there is rather small. This may also be taken as a proof that the values are reproducible by the method used. The highest value was found

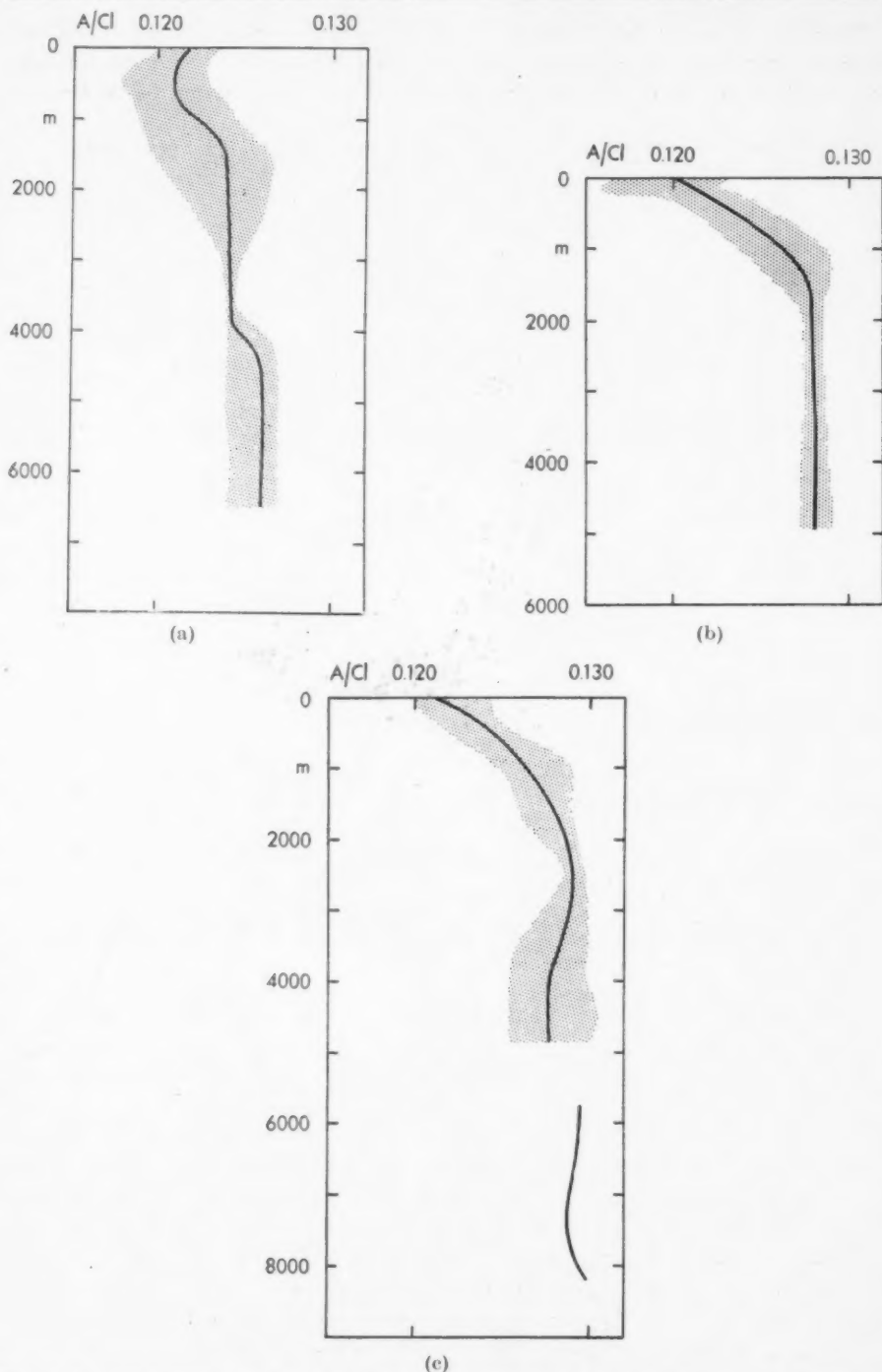


Fig. 2. The variation of the specific alkalinity with depth in (a) the Atlantic Ocean, (b) the Indian Ocean, and (c) the Pacific Ocean. The full-drawn line indicates the estimated average. The shadowed area gives the variation of the individual values.

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in the Pacific Ocean with 0.1285. The Indian Ocean holds, in the deep water, 0.1275 (from about 1,750 metres down). In the Pacific generally a decrease toward the bottom was found, but the values were there considerably scattered. The Atlantic holds, between 1,500 and 4,000 m, 0.1240, and the specific alkalinity increases in the bottom water to 0.1265.

The water close to the bottom which was investigated in the Indian and Atlantic Ocean shows very often increased values, as has been already pointed out by WATTENBERG for the Atlantic bottom waters. On the contrary, the bottom water in the Pacific generally shows a reduced value of 0.1270. An interesting property of waters in deep basins or trenches was detected in the Pacific Ocean. The specific alkalinity at 3,890 and 4,862 m at 7°38'S and 152°53'W is rather low with a value of 0.123.

VARIATIONS WITH TEMPERATURE

The warm surface waters in the equatorial region have a low specific alkalinity; they are oversaturated with carbonates in general to temperatures of 10°C. For the estimate of the carbonate saturation the solubility product determined by WATTENBERG was used. The deep and bottom waters with temperatures below 10°C are saturated with minor deviations from 100 per cent. In the Atlantic Ocean a slight oversaturation was found, except in the Antarctic bottom water, whereas in the other two oceans the waters are undersaturated by a few per cent, with the exception of the bottom water in the eastern part of the Pacific Ocean.

The temperature is, beside the carbon dioxide pressure, the most important factor determining the saturation of carbonates, and this influence is clearly reflected in the relationship of the specific alkalinity to the temperature. In all three oceans the specific alkalinity rises with decreasing temperature, below 10 to 11°C. The increase is not the same in the oceans investigated, which seems to be caused by the structure and the origin of the intermediate waters. The Indian Ocean presents the clearest picture. From a value of 0.120 at 10°C the increase in the specific alkalinity is linear toward the bottom temperature of 1.5°C. Near the bottom the values are scattered, and increase as well as decrease. By extrapolation to zero temperatures, a specific alkalinity of 0.130 is obtained. In the Pacific Ocean the specific alkalinity increases in two steps. The first increase goes from 12°C to 8°C and has a low gradient; the specific alkalinity rises from 0.121 to 0.123. From here the gradient becomes steeper, the specific alkalinity increasing from 0.123 at 6°C to 0.129 at 2°C. Again, as in the Indian Ocean, the values near the bottom scatter; maximum values of 0.131 are found, as are also the very low values at one Pacific station of only 0.123. By extrapolation of temperature specific alkalinity below 6°C to zero a value of 0.1305 is found, nearly the same as in the Indian Ocean. Quite different is the relation in the Atlantic Ocean. Here the specific alkalinity also rises with decreasing temperatures below 10°C, but attains at 8°C a value of 0.1235 which is constant down to temperatures of about 3°C; then it rises again with decreasing temperatures. By extrapolation to 0°C a value of 0.1305 is obtained.

VARIATION WITH OXYGEN CONTENT

The consumption of oxygen in the deep water is mainly caused by organic oxidation, whereby carbon dioxide is produced and its pressure increased, in this way causing

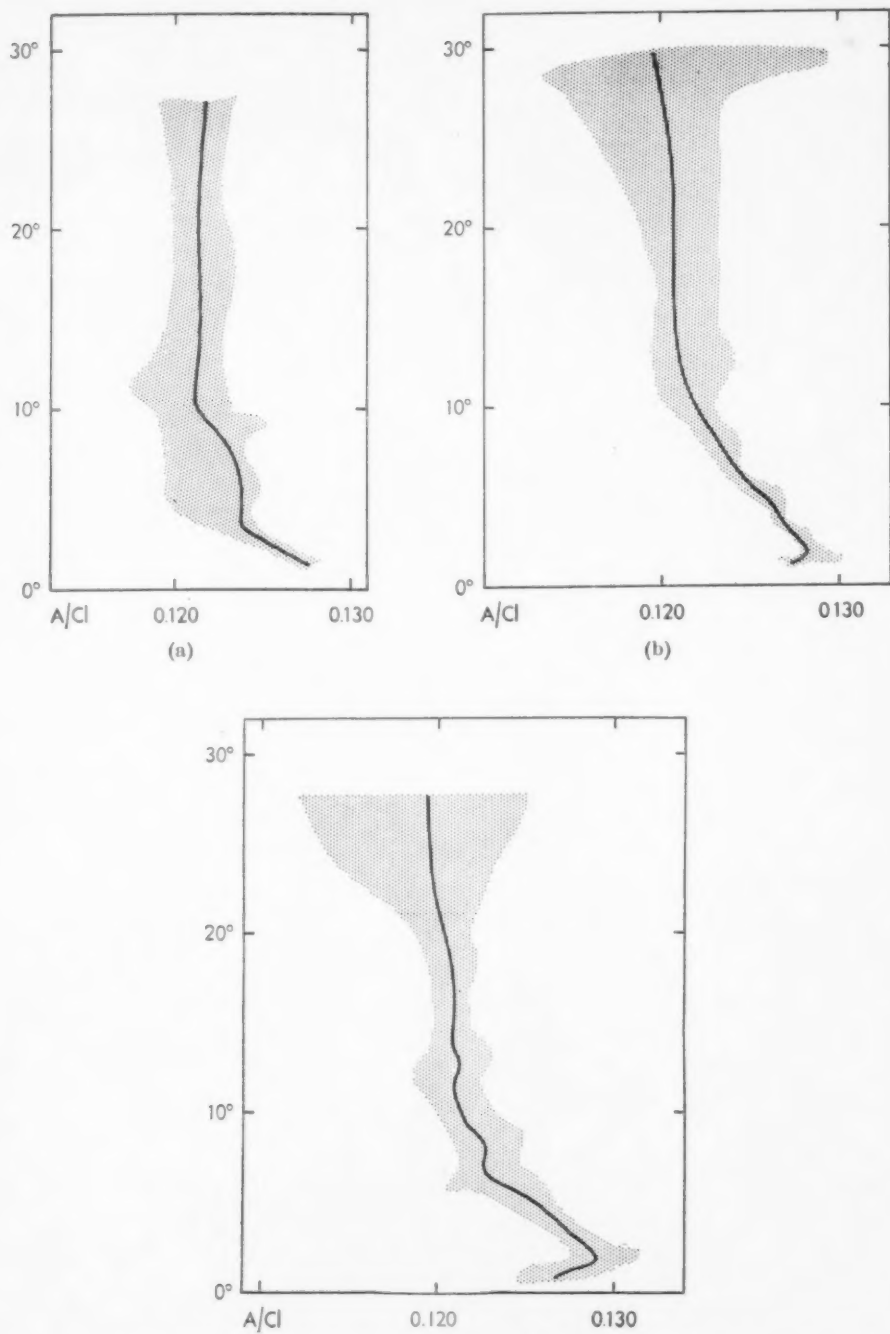


Fig. 3. The relationship between temperature and specific alkalinity in (a) the Atlantic Ocean, (b) the Indian Ocean, and (c) the Pacific Ocean.

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an increase of the solubility of carbonates. The specific alkalinity should, therefore, increase with the age of the water masses, the increased carbon-dioxide content, or increasing oxygen deficiency, since by the increased carbonate solubility the settling calcareous shells and the calcareous ooze on the bottom can be dissolved. The carbon-dioxide content is related to the carbonate system and largely depends upon the temperature and the depth, by which parameters the dissociation constants are changed. It seems, therefore, more appropriate to use the oxygen content as indicator for the organic oxidation; also the relationship cannot be very close, as the oxygen consumption is related to the oxygen decrease, and the original oxygen content hardly can be estimated with a high degree of certainty. Fig. 4 shows the relation

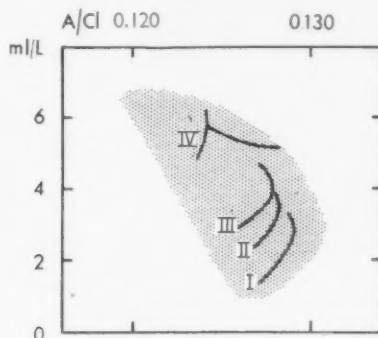


Fig. 4. The relationship of specific alkalinity to the oxygen content. The full-drawn lines denote the estimated mean relation in (i) the eastern Pacific Ocean, (ii) the western Pacific Ocean, (iii) the Indian Ocean, and (iv) the Atlantic Ocean. The shadowed area contains all values.

of the specific alkalinity below 1,500 m to the oxygen content. The highest values are found in the east Pacific Ocean where the oxygen content is lowest. The lowest values are found in the Atlantic Ocean correlated with a high oxygen content. The trend of the relation oxygen content specific alkalinity shows a marked difference in the Atlantic Ocean compared with the other region investigated. The difference is caused by the behaviour of the oxygen as well as by the specific alkalinity in the Atlantic. In the Atlantic a big water mass with low specific alkalinity exists below 1,500 m; high values are found only below 4,000 m. The oxygen content is, on the other hand, rather constant with values between 5 and 6 ml/L. In the other oceans the oxygen content increases with depth, whereas the specific alkalinity in general shows a maximum value above the bottom.

THE SPECIFIC ALKALINITY AS A PARAMETER FOR WATER MASSES

By the study of the specific alkalinity in its relation to the other hydrographic properties, the characteristic structure of the water masses in each ocean seems to be reflected in a characteristic distribution of the specific alkalinity with depth and temperature. In the Indian Ocean, where intermediate waters formed in the northern hemisphere do not exist, the relationship with depth is the simplest. On the contrary in the Atlantic, where the arctic deep current stretches far to the south and is of considerable thickness, the increase of the specific alkalinity with depth proceeds in two marked steps. In the Pacific Ocean a slight indication of the subarctic water masses can be detected.

The equatorial surface-waters, in which the main production of calcareous shells goes on, show a low specific alkalinity, the minimum values being about 0.115. The removed calcium is restored by vertical and horizontal mixing. In regions where the mixing processes are going on on a small scale the specific alkalinity attains very low values, as in the countercurrent in the Pacific Ocean. If, however, subarctic water masses are transported towards the equatorial region the temperature change will kill the organisms originally living in them and, if the horizontal intermixing with waters rich in warm-water organisms is low, the production of calcareous organisms will also be small. That seems to be the case in the eastern part of the north equatorial current, where a high specific alkalinity is found and the carbonate supersaturation should offer a good condition for lime-secreting animals.

The circumpolar water found in all three oceans shows a remarkable constancy of the specific alkalinity between 0.127 and 0.128. From the relationship between the hydrographic parameters and the specific alkalinity given above it follows that the specific alkalinity can be used in order to characterize water masses, when the *T-S* relation does not give reliable indications. In combination with the oxygen content, the salinity, and the temperature, the alkalinity gives a typical pattern for the different water masses.

The surface waters from the equatorial regions, which were the only ones investigated, show in general a low value of about 0.119. This is caused by the oversaturation in the carbonate content by the increased temperature and the accordingly increased activity of lime-secreting organisms. Low specific alkalinity is also found in the Red Sea (0.111 to 0.119). On the other hand the waters outflowing from the Mediterranean show a high specific alkalinity, which may be caused by the low productivity in this area. Surface waters with high values are found in the northern part of the Indian Ocean near Ceylon, where values of 0.123 to 0.129 were found in connection with low salinity. Another area with high values is found in the Panama Bay. Remarkable high surface values are found in the extension of the California current after it has been mixed with waters from the Gulf of Panama. The California current brings water from the arctic region and assembles the river water falling into the Pacific from the North American continent. The specific alkalinity in the countercurrent does not seem to be constant. Near the American coast, the values are high (0.121 to 0.123), but in the central regions they are low. The rain in the central part of the Pacific seems to be depleted of calcium, but not the precipitation originating from continental air masses. The surface values in the Atlantic are higher by about 0.002 than in the other two oceans investigated.

High surface values seem to be correlated with river water, upwelling water, and in some regions also with rain.

The highest values of specific alkalinity in deep waters are found in the Pacific Ocean between 2,000 and 4,000 metres with 0.128 to 0.129. The corresponding values in the Indian Ocean are 0.127 to 0.128, in the North Atlantic deep water only 0.124 but 0.126 in the South Atlantic deep water. The deep waters are saturated with lime within limits of 3 per cent. The waters in the Pacific and Indian Ocean are slightly undersaturated, whereas in the Atlantic they are slightly oversaturated. The maximum values of the specific alkalinity are found at higher levels in the eastern part of the oceans than in the western part; in the former at 2,000 m and in the latter

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at 4,000 m. The bottom water in the southern parts of all oceans has between 0.126 and 0.128. The Mindanao Trench shows a value of 0.129.

The bottom water at station 105, north of Tahiti, shows very interesting properties. The specific alkalinity is as low as 0.123. The salinity is the highest found in the bottom waters of the Pacific Ocean with a value of 34.90‰ which is about 0.2‰ over the general average. A faulty determination of depth is impossible, as the depth determination is carried out by unprotected thermometers in the deep series and the bottom temperature fits in well with the values generally found. The changes in the chemical composition must be ascribed to factors which have their origin in the environment. The bottom sediment of this place is pure red clay with the lime content zero; the pH in the sediment is about 6.9. It may, therefore, be concluded that on this place "volatiles," in the sense of RUBEY, are added to the bottom water. The volatiles containing an excess of anion should increase the chlorinity and reduce the alkalinity. However, in correspondence with this explanation of our findings is the fact that the pH is not lowered as should be expected.

In general it can be stated that waters recently mixed with river waters or rain of continental origin show high values. Old deep waters are also marked by a high specific alkalinity. Low values on the other hand are found in warm surface waters or waters originating from them.

In all surface waters investigated oversaturation of lime is found ranging from 110 to 156 per cent, whereas in deep waters the lime saturation is about 100 per cent. The intermediate waters are often undersaturated in respect to the lime content. The undersaturation is more developed in the Pacific Ocean than in the Indian Ocean. In the Atlantic Ocean only in rather few places was undersaturation observed. In the oceans of today the undersaturation with regard to lime is created by a high pressure of carbon dioxide which is set free by the decomposition of organic matter. Already WATTENBERG has pointed out this fact, which has very often been overlooked. Surface water in equilibrium with the carbon dioxide of the atmosphere can never become undersaturated with lime, and dissolved carbonate only by a lowering of the temperature. There must also be production of carbon dioxide which is the result of the decomposition of organic matter, or there must be an addition or liberation of carbon dioxide by the addition of volatiles. The carbon dioxide content is increased by a high rate of organic production in the surface waters and a low exchange of waters with the surface. In general such conditions are contradictory, as by a low vertical circulation the surface waters very soon become depleted in nutrient salts with following decrease in the rate of production. But if intermediate water is first moved upwards into the surface and then heated by insolation and moved over the intermediate water in horizontal direction, the conditions are given for the creation of a high pressure of carbon dioxide in the deeper waters. Such conditions are found in the region of the trade winds in the eastern part of the Pacific and the Atlantic Oceans; also near islands or archipelagos such conditions may be found to a smaller degree.

The rate of circulation in an ocean determines also the total content of carbon in the deep waters. The deep waters in the North Pacific Ocean show a high content of carbon dioxide and a low content of oxygen, which indicates a low rate of circulation.

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REFERENCES

- ANDERSSON D. H. and ROBINSON R. J. (1946) Rapid electrometric determination of the alkalinity of sea water. *Ind. and Eng. Chem. Anal. Ed.* **18**, 767.
- BRUNEAU L., JERLOV N. and KOCZY F. F. (1953) Physical and chemical methods. *Rep. Swed. Deep-Sea Exp.* **3**, 99.
- REVELLE R. (1944) Marine bottom samples collected in the Pacific Ocean. *Scient. Res. Cruise VII of Carnegie, Oceanography II*, 156.
- RUBEY W. W. (1951) Geologic history of sea water. *Bull. Geol. Soc. Amer.* **62** 1111-1147.
- THOMPSON T. G. and BONNER R. U. (1931) *Ind. and Eng. Chem. Anal. Ed.* **3**, 393.
- THOMPSON T. G. and ANDERSSON D. H. (1940) The determination of the alkalinity of sea water. *J. Marine Res. Sears Found.* **3**, 224.
- WATTENBERG H. (1933) Über die Titrationsalkalinität und den Kalziumkarbonatgehalt des Meereswassers. *Wiss. Erg. der Deutsch. Atlant. Exped. Meteor* **8**, 122.
- WIESE W. (1930) Zur Kenntnis der Salze des Meereises. *Ann. Hydr.* **58**, 282.

INSTRUMENTAL NOTE

A piston coring device

(Received 7 March 1956)

A PISTON coring tube has been developed at the Department of Oceanography, University of Washington, Seattle. This device operates on the general principles of the Kullenberg coring tube but eliminates some of its disadvantages. An automatic cable-clamping device, termed the piston immobilizer, has been developed, and prevents the upward movement of this piston after penetration into the sediments has ceased. The use of this device prevents the drawing in of large quantities of sediments from a single level, virtually eliminates the breaking of the core in sections, and minimizes core distortion. An improved core retainer has also been developed. This is a flapper valve-type retainer and is an integral part of the nosepiece wall. The advantages of this feature over the normal "orange-peel" retainer are that it does not extend beyond the wall surface during corer penetration and that it is more positive in retaining the core. These features, plus the half-inch-wall core barrel, tapered acme-thread core-barrel couplings, and other minor modifications, make this coring tube effective for both deep- and shallow-water operations. Cores approximately 60 feet long have been taken.

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LETTER TO THE EDITORS

Note on a Temperature-Depth Measurement

THE temperature vs. depth measurement reproduced below Fig. 1 was made south of Cuba (Lat. $19^{\circ}45'N$, Long. $76^{\circ}15'W$) on 6 April, 1956, in an effort to study the thermal details of the thermocline at higher sensitivity than is afforded by the bathythermograph. The temperature measurement was made with a thermistor working into a conventional Wheatstone bridge and commercial recording equipment. The depth is estimated from wire out and surface wire angle since the associated depth meter malfunctioned. Instrumental noise is about $0.0001^{\circ}C$. The curve marked "down" is the record obtained while lowering and "up" was recorded while retrieving. These curves are arbitrarily displaced on the depth scale from the "average" obtained from them and are reproduced to show the differences in detail obtained in the two. The weather was very calm and the roll very

slight. Unfortunately the planned series of measurements to determine the size and shape of these irregularities could not be completed, so this one lowering is presented here as an indication of the noisy and erratic nature of the thermocline when examined with instruments of high sensitivity.

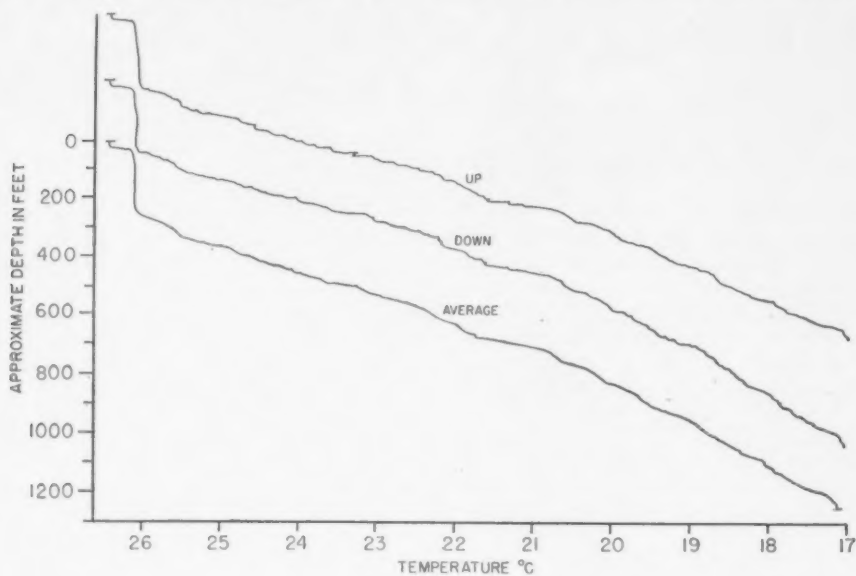


Fig. 1.

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts.

WILLIAM S. RICHARDSON

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IN MEMORIAM

Henry Crosby Stetson

HENRY STETSON died at sea on 3 December 1955, on board the research vessel *Atlantis*, off the coast of Chile.

HENRY was born on 10 October 1900, in Cambridge, Massachusetts. As a youth he visited the coast of Maine during summer vacations and observed shore processes and marine life. On one occasion, when he was at sea with a local lobsterman on a particularly stormy day, he was able to continue the work of hauling lobster traps when the lobsterman's own sons were too seasick to carry on. These early experiences laid the foundation for a career as one of the pioneers in geological oceanography.

In college at Harvard University, HENRY majored in geology and began to specialize in palaeontology under the direction of Professor PERCY E. RAYMOND. He became assistant curator in palaeontology at the Museum of Comparative Zoology in 1928. His first scientific studies, on trilobites, anaspids, and fossil fishes, went beyond their taxonomy to questions of distribution and physical environment. During the next few years his investigations turned more definitely into the field of the environment. From his Friendship sloop, the *Neva*, he made observations of water temperatures in Massachusetts Bay and the Gulf of Maine for HENRY B. BIGELOW, and he collected samples of the bottom sediments of Massachusetts Bay. On several of the cruises he was accompanied by WILLIAM SCHEVILL and COLUMBUS ISELIN. Using the developing techniques of quantitative sedimentary petrography, he contributed information which required revision of text-book statements regarding the gradation of sediment-particle size in relation to depth of water and distance from shore. Other studies included unusual processes of sedimentation - the flotation of unwetted sand grains on the sea surface, and the transportation of sand in organic jelly-like masses.

When the Woods Hole Oceanographic Institution was established, HENRY STETSON was selected for the staff position in submarine geology. For the next several years he carried on a programme of research on many aspects of marine sedimentation and on the submarine canyons off the Atlantic coast of the United States. This included many cruises on the research vessel *Atlantis* and on other vessels of the institution, and the supervision of work of graduate students and fellows in submarine geology at the institution.

During World War II HENRY was engaged in a number of projects for the U.S. Navy and the Joint Chiefs of Staff. Much of that work can never be publicly recognized, but those who were associated with him can attest to the value of the services he rendered. The pressure of the war-time work, which included long hours in the laboratory and office as well as a great deal of activity at sea, may have been a factor in causing his death at the age of 55.

After the war HENRY continued as senior geologist of the Woods Hole Oceanographic Institution. He was chief scientist in charge of two expeditions to the Gulf of Mexico, and he continued his work in the Atlantic. He was Louis Agassiz Fellow in Oceanography at the Museum of Comparative Zoology in Cambridge, Massachusetts, where he taught a course in marine geology at Harvard University.

HENRY's scientific work was done with extreme care and attention to detail, and his interpretations were conservative. The many items in his bibliography are a partial record of his excellent work. He was a Fellow of the Geological Society of America, and a member of the American Geophysical Union, the American Association of Petroleum Geologists, the Society of Economic Palaeontologists and Mineralogists, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences.

On his last cruise he was chief scientist on an expedition to the eastern Pacific Ocean. A heart attack brought an end to a productive career. HENRY died at sea, with his boots on, while engaged in the work he loved.

He is survived by his wife, EDITH and three children: ROBERT, THOMAS and EDITH.

J. L. HOUGH

Urbana, Illinois

BIBLIOGRAPHY OF HENRY CROSBY STETSON

- 1927, The distribution and relationship of the Trinucleidae. *Bull. Mus. Comp. Zool., Harvard Univ.*, **68** 85-104.
- 1927, *Lasanius* and the problem of vertebrate origin. *J. Geol.*, **35**, 247-263.
- 1928, A restoration of the anaspid *Birkenia elegans* Traquair. *J. Geol.*, **36**, 458-470.
- 1928, A new American *Thelodus*. *Amer. J. Sci.*, **16**, 221-231.
- 1929, Report from the department of palaeontology. *Harvard College Mus. Comp. Zoology Ann. Rept.* (1928-29), 24-26.
- 1930, Notes on the structure of *Dinichthys* and *Macropetalachthys*. *Bull. Mus. Comp. Zool., Harvard Univ.*, **71** (2), 19-39.
- 1931, Report from the department of palaeontology. *Harvard College Mus. Comp. Zoology Ann. Rept.* (1930-31), 32-34.
- 1931, Studies on the morphology of the Heterostraci. *J. Geol.*, **39** (2), 141-154.
- 1932, Marine sediments and their significance. *Boston Soc. Nat. Hist. Bull.*, **62**, 12-17 (2 figs.).
- 1933, Scientific results of the *Nautilus* Expedition, 1931, under the command of Captain Sir Hubert Wilkins; V. The bottom deposits. *Pap. Phys. Oceanogr., Meteorol.*, **2** (3), 17-37.
- 1933, Sediments of the continental shelf off the northeastern United States (abstract). *Geol. Soc. Amer. Bull.*, **44**, 206-207.
- 1934, Origin and limits of a zone of rounded quartz sand off the southern New England coast. *J. Sed. Petr.*, **2** (3), 152-153.
- 1935, Bed-rocks from the canyons off Georges Bank (abstract). *Proc. Geol. Soc. Amer.*, (1934), 112.
- 1935, Bed-rocks from the continental margin on Georges Bank. *Trans. Amer. Geophys. Union*, 16th Ann. Meet., 226-228.
- 1936, Age of the submarine valleys off the central Atlantic coast (abstract). *Geol. Soc. Amer. Proc.* (1935), 108-109.
- 1936, The fossil mammal-reptile-fish and amphibian collections. *Notes concerning the history and contents of the Museum of Comparative Zoology, Cambridge*, 79-83.
- 1936, Review: Morphologie des Atlantischen Ozeans: Pt. 1. Die Tiefenverhältnisse des offenen Atlantischen Ozeans. *Rept. Meteor Exped.*, **3**, 1935. *Geogr. Rev.*, July, 1936, 513-516.
- 1936, Review: Report of the Snellius Expedition: Geological interpretation of bathymetric results, **5** (1), 1936. *Geogr. Rev.*, Oct, 1936, 702-703.
- 1936, Geology and palaeontology of the Georges Bank canyons: 1. Geology. *Bull. Geol. Soc., Amer.*, **47**, 339-366.
- 1936, Dredge-samples from the submarine canyons between Hudson Gorge and Chesapeake Bay. *Trans. Amer. Geophys. Union*, 17th Ann. Meet., 223-225.
- 1937, Current-measurements in the Georges Bank canyons. *Trans. Amer. Geophys. Union*, 18th Ann. Meet., 216-219.
- 1937, Further investigations of the submarine valleys of the Georges Bank (abstract). *Geol. Soc. Amer. Proc.*, June, 1936, 105.
- 1938, German and Austrian papers on mechanical analysis and papers dealing with sediments and sedimentation since 1933. *Nat. Res. Council, Div. Geol. Geogr., Rept. Comm. Sedimentation*, 28-36.
- 1938, Submerged valleys of the continental margin. *Appalachia*, n.s., **4** (7), 37-47.
- 1938, Present status of the problem of submarine canyons. *Proc. Amer. Phil. Soc.*, **79** (1), 27-33.
- 1938, The sediments of the continental shelf off the eastern coast of the United States. *Pap. Phys. Oceanogr., Meteorol.*, **5** (4), 1-48.
- 1939, Summary of sedimentary conditions on the continental shelf of the east coast of the United States. In *Recent Marine Sediments*. *Publ. Amer. Assoc. Petr. Geol.*, 230-240.
- 1940, Submarine geology. *Harvard Alumni Bull.*, **42** (13), 420-424.
- 1940, Depositional environments of sedimentary rocks. *Geogr. Rev.*, **30** (3), 480-484.
- 1941, Oceanography: Chapter in *Geology, 1888-1938, Fiftieth Anniversary Volume*, Geological Society of America, 43-69.
- 1942, Recent papers dealing with marine sediments and sedimentary processes. *Report of the committee on sedimentation, Nat. Research Council, Div. Geology and Geography Ann. Rept.*, 35-39.
- 1949, The sediments and stratigraphy of the east coast continental margin: Georges Bank to Norfolk Canyon. *Pap. Phys. Oceanogr., Meteorol.*, **11** (2), 1-60.
- 1953, The sediments of the western Gulf of Mexico: 1. The continental terrace of the western Gulf of Mexico: Its surface sediments, origin and development. *Pap. Phys. Oceanogr., Meteorol.*, **12** (4), 1-45.

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- 1953, Memorial to Percy Edward Raymond (1879-1952). *Proc. Geol. Soc., Amer. Ann. Rept.*, 1952, 121-126.
- 1954, A preliminary investigation of shifting beach profiles. *Coastal Geogr. Conf.*, 18 Feb., 1954, 57-62.
- 1955, The continental shelf. *Scientific American*, **192** (3), 82-86.
- 1955, Patterns of deposition at the continental margin. *Pap. Mar. Biol. and Oceanogr., Deep-Sea Res.*, Suppl. to Vol. **3**, 299-308.
- STETSON, H. C. and PARKER, F. L. (1942), Mechanical analysis of the sediment and the identification of the Foraminifera from the building excavation: The Boylston Street Fishweir, 2. *Papers of Robert S. Peabody Foundation for Archaeology*, 41-42.
- STETSON, H. C. and PHLEGER, F. B. (1947), Oceanography as related to petroleum geology. *Bull. Amer. Assoc. Petr. Geol.*, **31** (1), 175-178.
- STETSON, H. C. and SCHALK, M. (1935), Marine erosion of glacial deposits in Massachusetts Bay. *J. Sed. Petr.*, **5** (1), 40-51, 2 text figs.
- STETSON, H. C. and SMITH, J. F., (1937) Behaviour of suspension currents and mud slides on the continental slope. *Amer. J. Sci.*, **5** (35) (205), 1-13, 2 text figs.
- STETSON, H. C. and UPSON, J. E. (1937), Bottom deposits of the Ross Sea. *J. Sed. Petr.*, **7** (2), 55-66.
- BARBOUR, T. and STETSON, H. C. (1929), The squamation of *Homoeosaurus*. *Bull. Mus. Comp. Zool., Harvard Univ.*, **69**, 97-134.
- RAYMOND, P. E. and STETSON, H. C. (1931), A new factor in the transportation and distribution of marine sediments. *Science*, **73** (1882), 105-106.
- RAYMOND, P. E. and STETSON, H. C. (1932), A calcareous beach on the coast of Maine. *J. Sed. Petr.*, **2** (2), 51-62.
- TRASK, P. D., PHLEGER, F. B. and STETSON, H. C. (1947), Recent changes in sedimentation in the Gulf of Mexico. *Science*, **106** (2759), 460-461.

NEWS AND NOTES

On the distribution and origin of the deep-sea bottom fauna

Au moment où étaient mises en oeuvre les données rapportées par l'Expédition Suédoise (*Albatross*), l'Expédition Danoise (*Galathea*) l'Expédition Soviétique d'exploration des grandes profondeurs, le Professeur R. SPÄRCK, président du 14e Congrès international de Zoologie, eut l'heureuse initiative d'organiser, en marge de ce Congrès et sous l'égide de l'U.I.S.B., un Colloque sur l'origine et la distribution de la faune benthique profonde des Océans. C'était en quelque sorte faire le point de nos connaissances sur un sujet qui recevrait son plein développement dans les comptes rendus scientifiques des récentes Expéditions. Tenu à Copenhague au mois d'Aout 1953, ce colloque dont le texte vient d'être publié* s'est ouvert par une intervention du Prof. SVEN EKMAN qui, s'appuyant spécialement sur la répartition des Echinodermes abyssaux, montre que ceux-ci sont différemment répartis dans les fosses des trois Océans : 2-7% des espèces seulement se rencontrent à la fois dans les Océans Indien, Pacifique et Atlantique. Cette localisation, qui d'ailleurs n'est pas le fait de l'ensemble de la faune et en particulier des espèces passant au cours de leur développement par des stades pélagiques, peut être déterminée, pour des formes sténothermes, par les faibles différences de température observées dans les diverses régions et entretenues par les courants profonds venant de l'arctique ou de l'antarctique canalisés par les crêtes sous-marines. De telles barrières sont un obstacle notamment à des échanges de faune entre l'Océan Atlantique, d'une part avec l'Océan Indien et, d'autre part, avec l'Océan Pacifique.

Préciser les conditions de vie offertes à la faune benthique abyssale a été précisément la tâche du Prof. LOUIS FAGE qui a envisagé tour à tour la nature et la constitution du substratum, les caractéristiques de l'eau qui le recouvre, les pressions que supportent ses habitants et les sources de nourriture mise à leur disposition. Sa conclusion est que les êtres abyssaux vivant sous une énorme pression, dans l'obscurité totale, à très basse température, sur une vase molle, fortement radioactive, pauvre en calcaire, riche en silice, baignée par une eau à teneur en oxygène réduite et n'ayant à leur disposition qu'une quantité relativement faible de nourriture sont soumis à des systèmes d'échange très particuliers qui aboutissent à un ralentissement de leur activité et de leur métabolisme et imposent une sévère sélection. L'absence de faune proprement abyssale en Méditerranée, la grande proportion de formes eurybathes dans les mers polaires semblent prouver qu'une des caractéristiques les plus importantes des grands fonds, tant au point de vue physiologique qu'au point de vue de la constitution de la faune abyssale est la température constamment basse qu'on y trouve.

Par son intervention sur la présence de bactéries dans les grandes profondeurs, présence mise en évidence par l'examen des sédiments recueillis à plus de 6,000 m de profondeur par la *Galathea*, le Dr. CLAUDE E. ZO BELL pose précisément la question de la quantité de nourriture dont peuvent disposer les êtres abyssaux mangeurs de vase. D'après les premières investigations dont le Dr. ZO BELL fait état, il paraît résulter qu'au moins 0,88 g de carbone organique peut être produit, par mètre carré et par an, par les bactéries du fond ce qui est une quantité relativement importante. Mais le Dr. G. THORSON faisant remarquer que toutes les observations tendent à prouver que, néanmoins, sur ces fonds, la faune des Invertébrés est extrêmement pauvre, il faut donc admettre que les bactéries n'entrent que pour une faible part dans leur nourriture. En réalité, de l'avis des orateurs, on ne possède encore sur ce point que des données trop fragmentaires pour en tirer des conclusions valables. Ce qui est certain, c'est la présence de bactéries en nombre non négligeable vivant aux plus grandes profondeurs.

Le Dr. JOHN D. H. WISEMAN, se basant sur ses études sur les Foraminifères planctoniques, expose ensuite les méthodes qui permettent de fixer l'âge d'un dépôt quelconque, en corrélation avec les changements des climats intervenus dans le passé.

*Union internationale des Sciences biologiques, 1954, Série B, n° 16, 89 p.

Différents orateurs passent ensuite en revue les principales caractéristiques de la distribution géographique des groupes abyssaux les plus importants. Mr. F. JENSENIUS MADSEN et le Professeur TORSTEN GISLEN traitent des Echinodermes. Cette faune se compose d'une part d'un petit nombre d'espèces communes et d'autre part, d'un grand nombre d'espèces relativement rares. Quant à leur répartition on peut noter que les formes les plus profondes se répartissent assez bien suivant deux régions principales : Atlantique et Indien d'une part et Pacifique d'autre part. Toutefois au moins un tiers des Ophiures, environ la moitié des Holothuries et plus de la moitié des Astéries des profondeurs extrêmes ne sont connus que d'une seule localité. Notons qu'une Synapte du genre *Myriotrochus* a été capturée dans la fosse des Philippines par 10,200 m de profondeur. Quant aux Crinoïdes, leur nombre diminue très rapidement au-dessous de 1,000 m, probablement en raison du fait qu'il s'agit de formes fixées ne pouvant se nourrir que de particules en suspension. La *Galathea* a cependant capturée à 8,300 m un représentant de la famille des Bathycrinidae.

C'est également à 8,200 m dans la fosse de Kermadec que git le Polychète le plus profond ; Mr. J. B. KIRKEGAARD l'a trouvé dans les matériaux rapportés par la *Galathea*. En fait 111 espèces sont actuellement connues comme vivant exclusivement au-dessous de 2,000 m.

Les Crustacés, dont a parlé le Dr. ERIK DAHL, sont représentés par nombre d'espèces jusqu'aux grandes profondeurs explorées, mais quelques genres seulement sont exclusivement cantonnés dans la zone abyssale proprement dite, et, si les formes à larves pélagiques ont une vaste répartition horizontale, il n'en est pas de même de beaucoup de Pécarides et de Cirripèdes benthiques.

D'après le Professeur LOUIS FAGE, les Pycnogonides abyssaux, dont il donne la liste, appartiennent à des genres eurybathes, la plupart nombreux en espèces et tous bien représentés dans les mers froides, ou certains d'entre eux vivent là dans la zone littorale ou côtière. Plus de 40 espèces ont été trouvées dans les grands fonds où vivent également les Spongiaires et Coelentérés qui sont, au moins dans la zone côtière et archibentale, leur nourriture habituelle. Aussi, constituent-ils un élément important de la faune des grandes profondeurs océaniques. Les espèces cosmopolites sont relativement rares, actuellement nous n'en connaissons que trois qui toutes appartiennent au genre *Colossendeis*.

Le Dr. MARION GREY, dressant la liste des Poissons capturés audessous de 3,660 m, note la difficulté de savoir si les 37 espèces citées, dont 21 ne sont connues que par un, deux ou trois exemplaires, sont exclusivement benthiques. Il est possible que parmi elles se trouvent des formes bathypélagiques. Parmi ces 21 espèces dominent les Macrouridae et les Brotulidae. Le Dr. CARL L. HUBBS, essayant de préciser la répartition géographique des Macrouridae, signale que la localisation de beaucoup d'espèces semble aussi prononcée que pour les poissons côtiers. Pour les Brotulidae, le Dr. ORVAR NYBELIN arrive aux mêmes constatations : une seule espèce est commune à l'Océan Indien et au Pacifique, aucune ne se trouve à la fois dans l'Océan Indien et l'Atlantique, ainsi aucune n'est commune aux trois Océans.

Enfin, le Professeur L. A. ZENKEWITCH communique quelques résultats de l'Expédition soviétique qui a exploré les grandes fosses des Kuriles-Kamtschatka atteignant 10,382 m. Après avoir dressé un tableau de la répartition verticale des principaux groupes récoltés, il constate que si à 9,800 m ont été recueillis seulement des Polychètes, des Echiurides, des Holothuries et des Pogonophorides, ces organismes peuvent s'y trouver en très grand nombre : 2850 exemplaires de deux espèces d'Holothuries, 2000 exemplaires de deux espèces de *Pogonophora*, 85 Echiurides, 150 Crinoïdes et 160 Polychètes, en tout 5700 exemplaires. Une des acquisitions les plus remarquables de ces dragages profonds a été la découverte d'un grand nombre de formes nouvelles, en particulier de 16 représentants de Pogonophorides qui n'étaient jusque là connus que par une seule espèce et qui comptent maintenant 4 familles distinctes. Bon exemple de la localisation géographique de certaines formes abyssales à ajouter à ceux que fournissent les poissons du Nord Pacifique étudiés par le Prof. T. RASS.

En conclusion de ce Colloque et après de pertinentes observations du Dr. ANTON F. BRUUN sur les facteurs pouvant agir sur la distribution des espèces bathyales, le Prof. R. SPÄRCK signale qu'il n'existe pas de différences morphologiques essentielles entre les espèces du plateau continental et les espèces abyssales qui ne sauraient être considérée comme des représentants d'une faune spécialement ancienne, bien qu'elle comprenne quelques formes archaïques qui ont mieux survécu dans ce milieu particulier. Il s'agit de formes aptes à pénétrer dans les grandes profondeurs et à s'adapter aux conditions écologiques qui y règnent. Peut-être ces possibilités sont elles plus grandes pour les espèces arctiques, et ce processus se continue-t-il de nos jours. En tout cas cette faune n'est pas une faune originaire d'une région déterminée des Océans, elle représente une sélection de quelques

espèces de la faune côtière qui ont pu gagner les profondeurs et, en raison des conditions rencontrées, s'y répandre parfois sur une large étendue.

Nous espérons trouver dans la publication complète des résultats des récentes Expéditions Suédoises, Danoises et Soviétiques, la réponse à beaucoup de questions abordées au cours de ce colloque et la possibilité de dresser, avec l'expérience acquise, le programme précis de futures recherches dans ce domaine.

*Museum d'Histoire Naturelle,
Laboratoire de Zoologie,
Paris.*

LOUIS FAGE

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1955-56

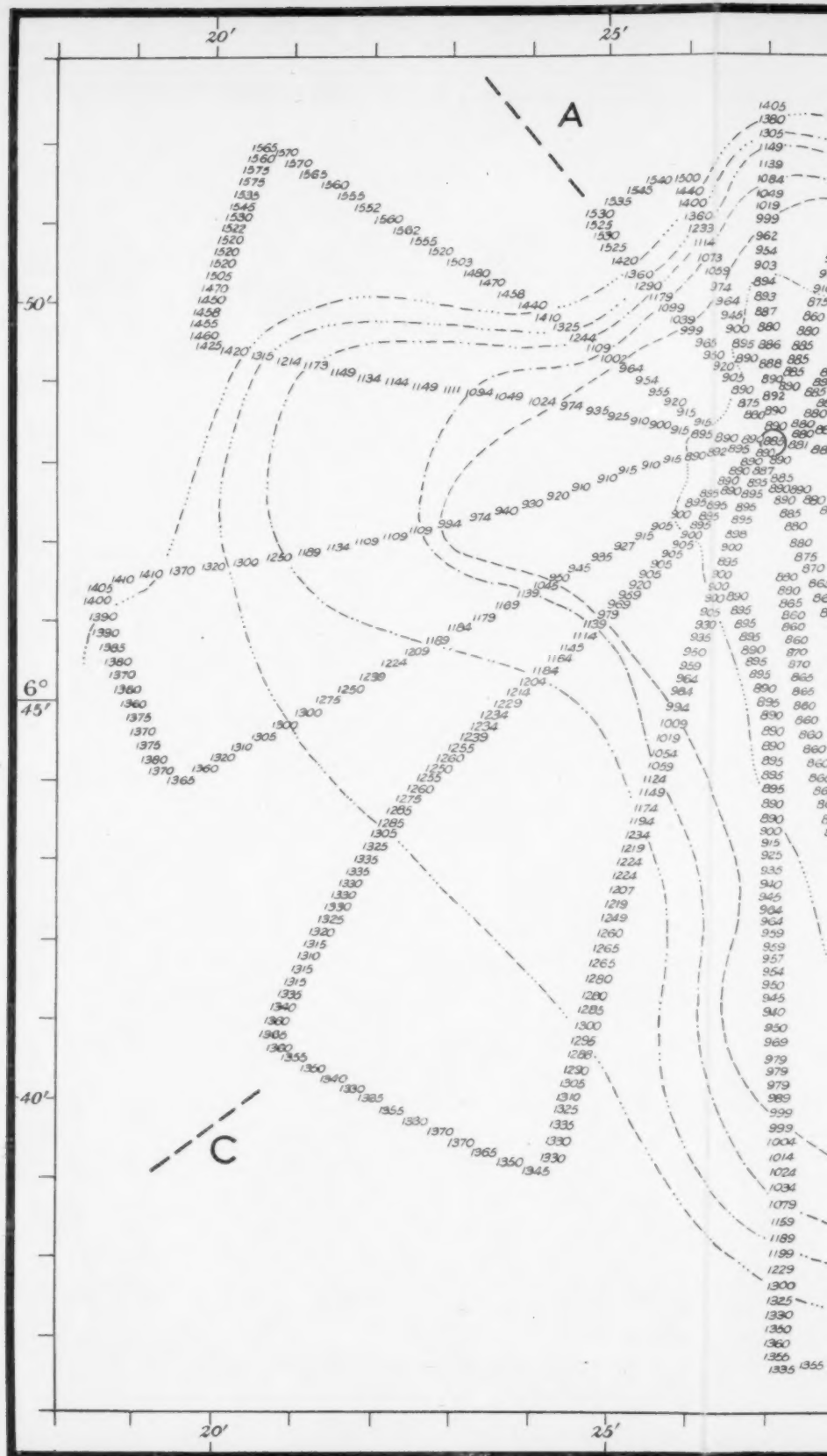
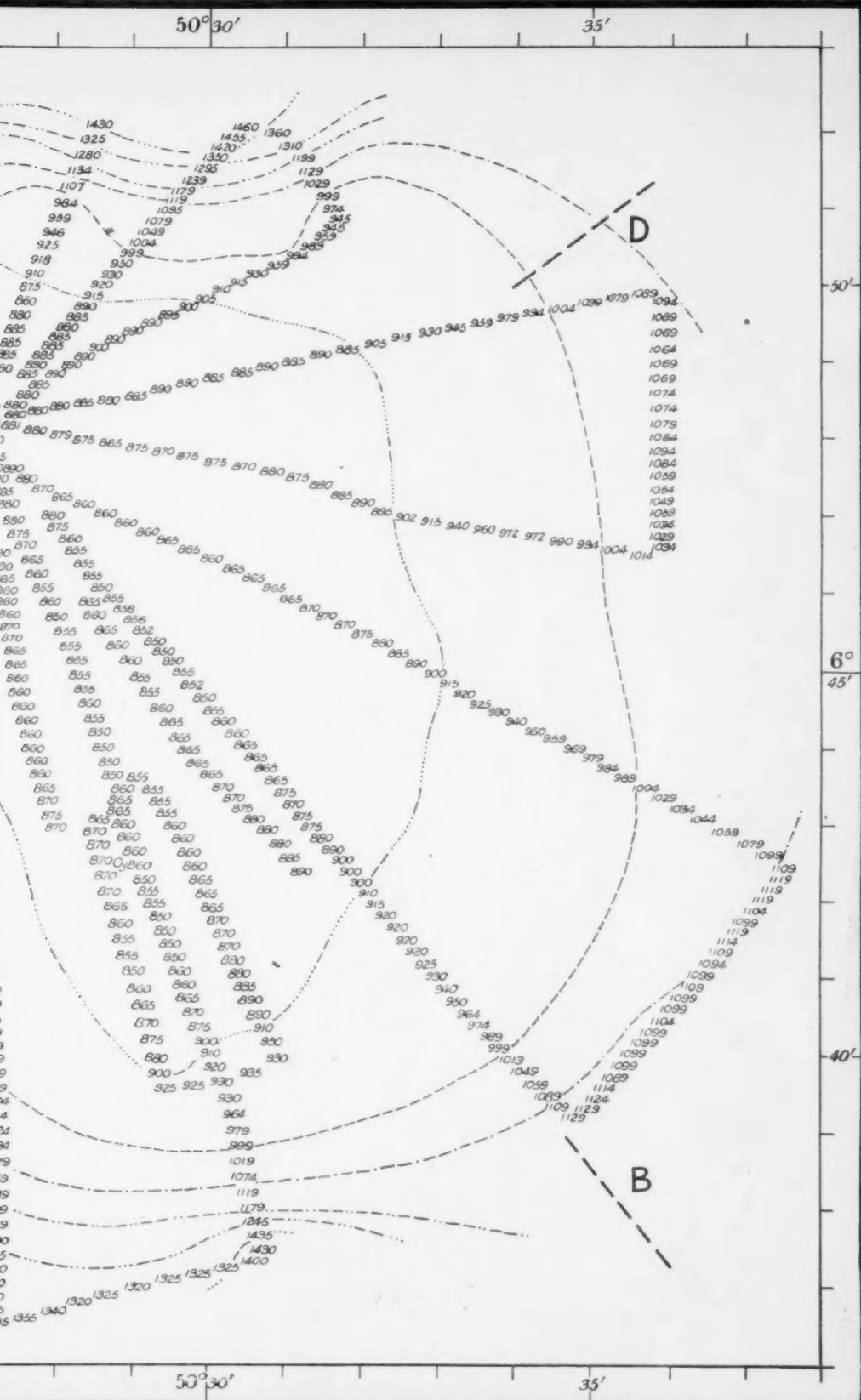


Fig. 3. Survey of Andrew Tablemount. Scale 1 : 144,000 ; contour



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contour interval 100 fm. ; soundings corrected by Matthews' (1939) tables.

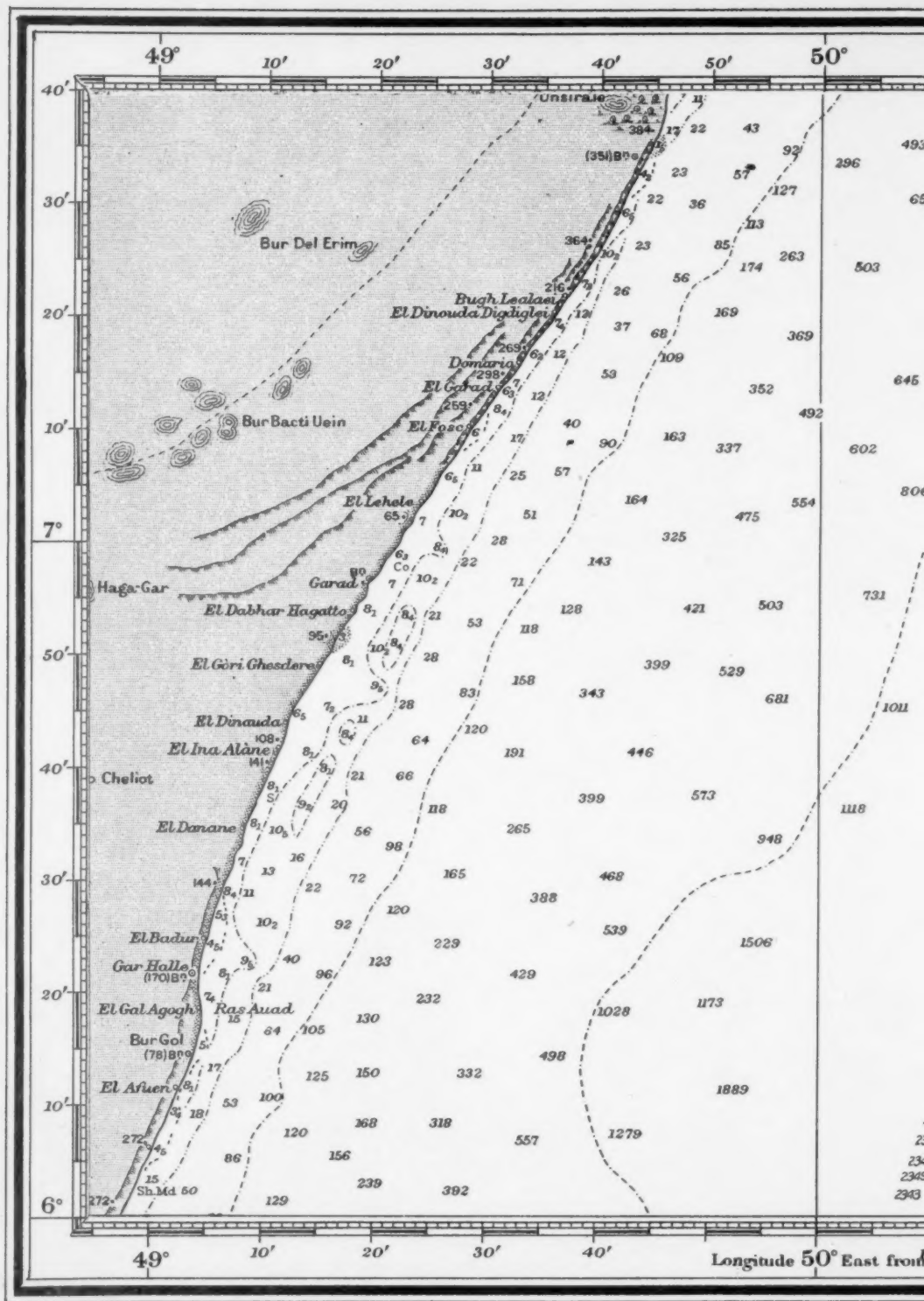
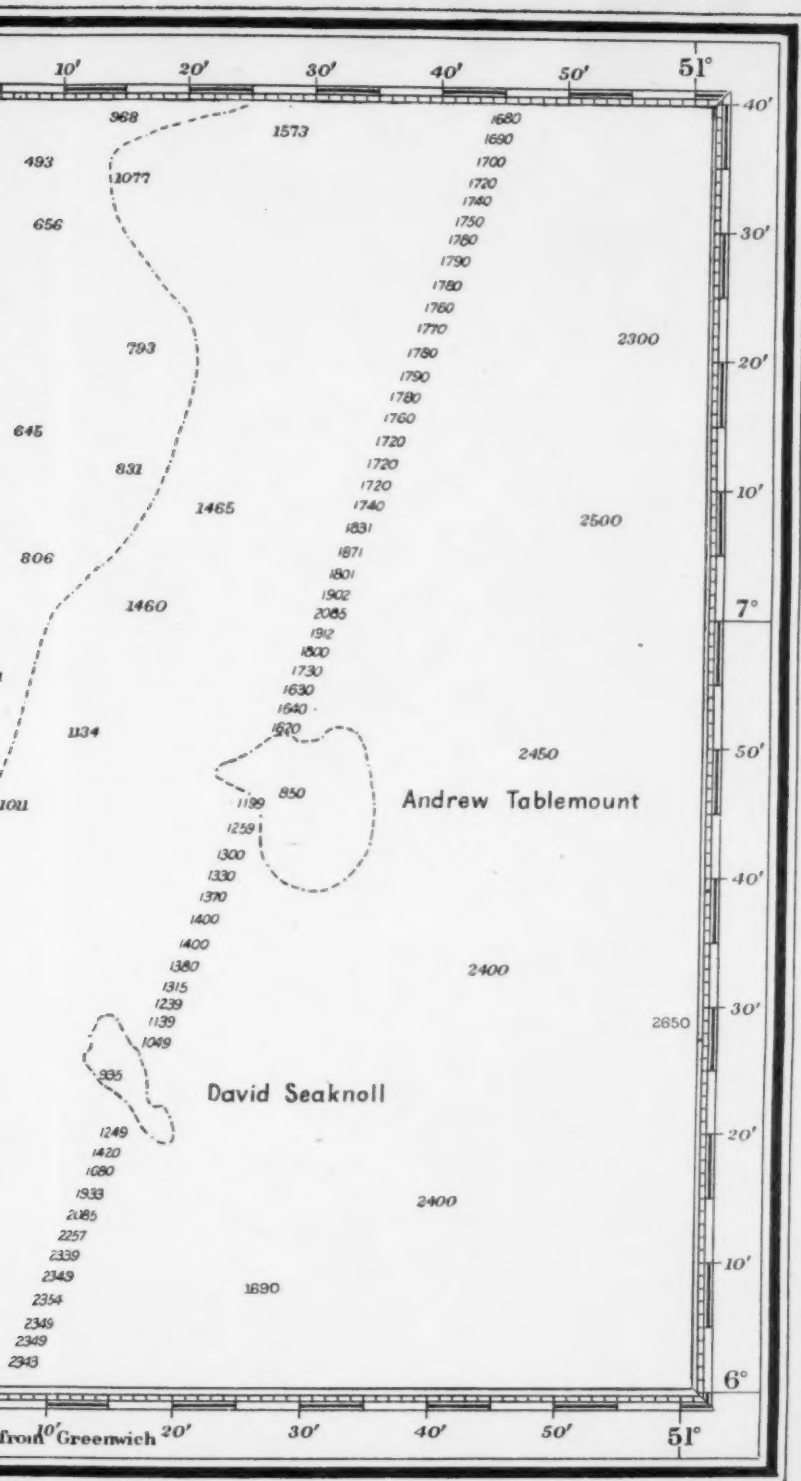


Fig. 2. Portion of Admiralty Chart No. 2953 with sounding line soundings corrected by



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by Matthews' (1939) tables taken by H.M.S. Dalrymple.

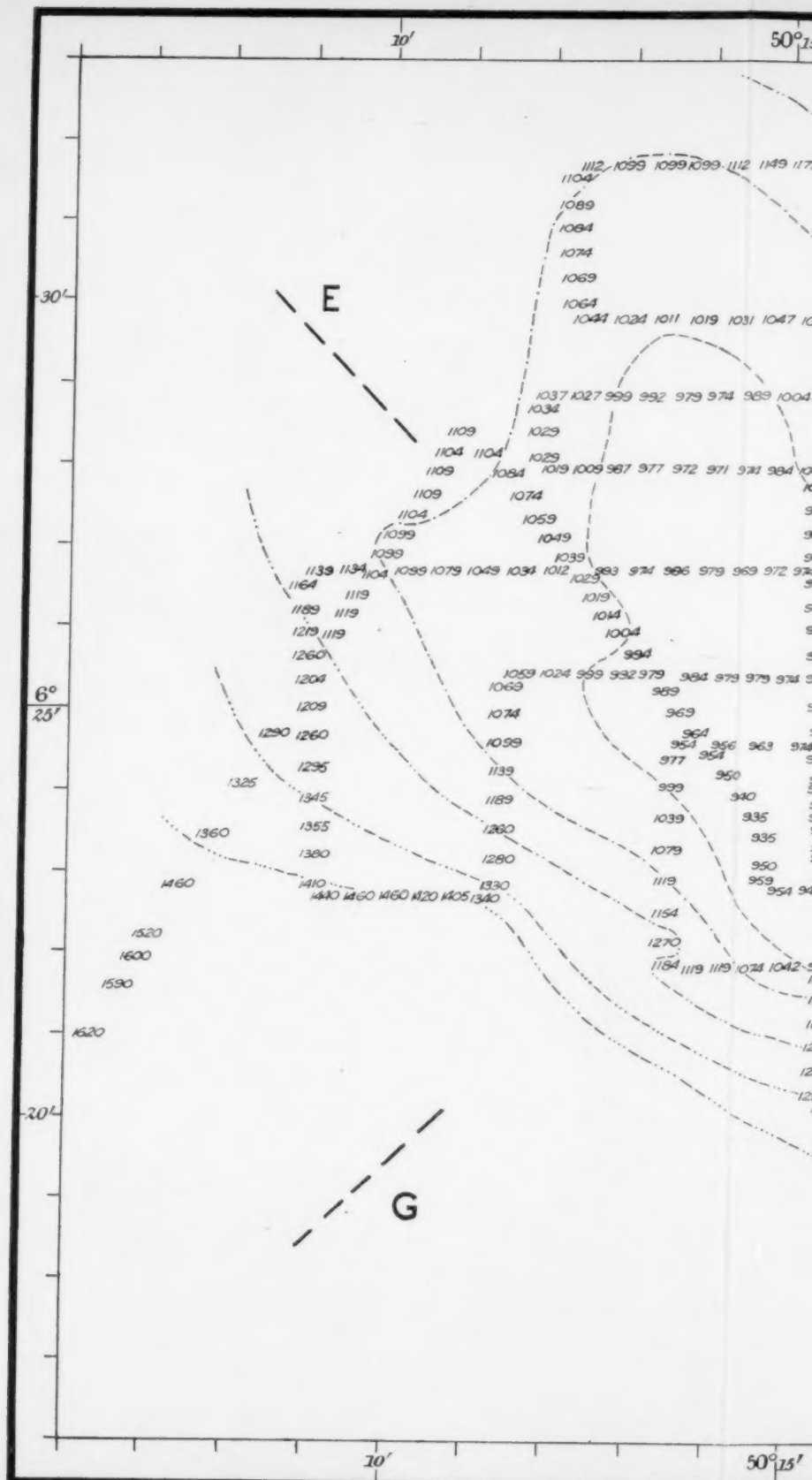


Fig. 5. Survey of David Seaknoll. Scale 1 : 144,000 ; contour

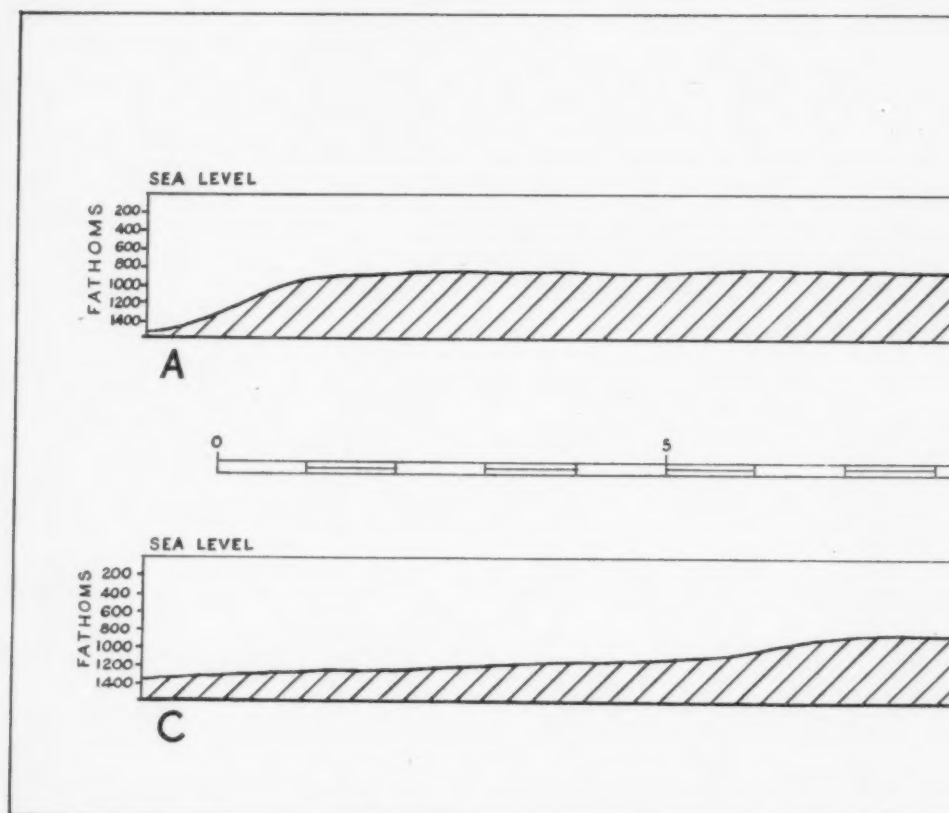
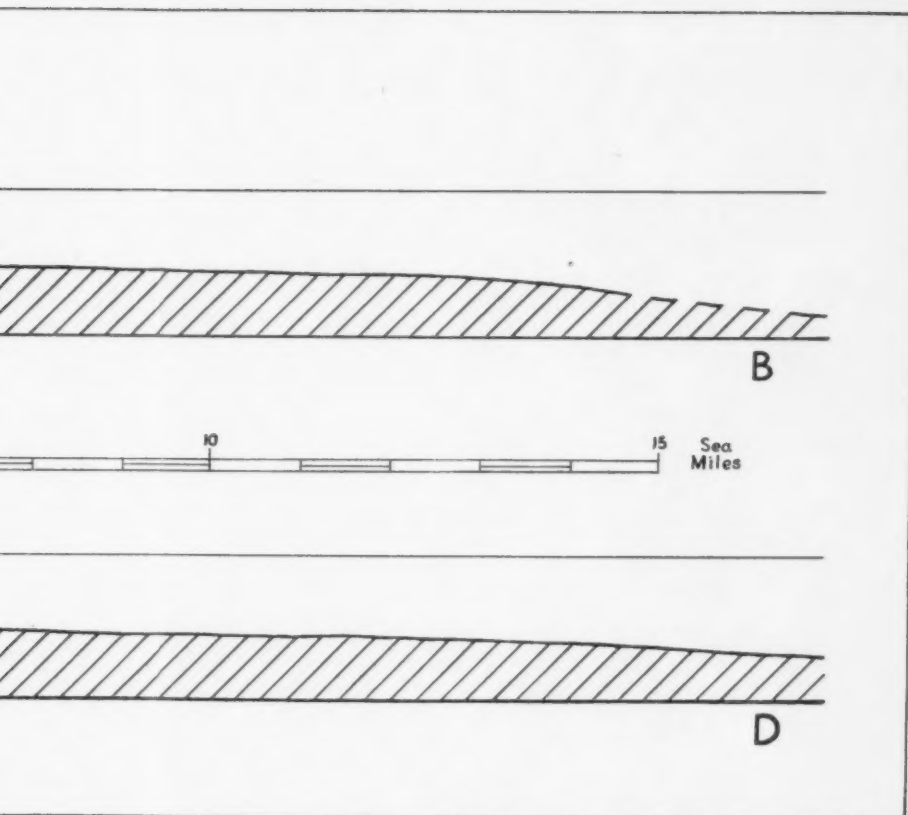


Fig. 4. Natural profiles through Andrew Tablemount s



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unt showing flat top and steep northwesterly slope.

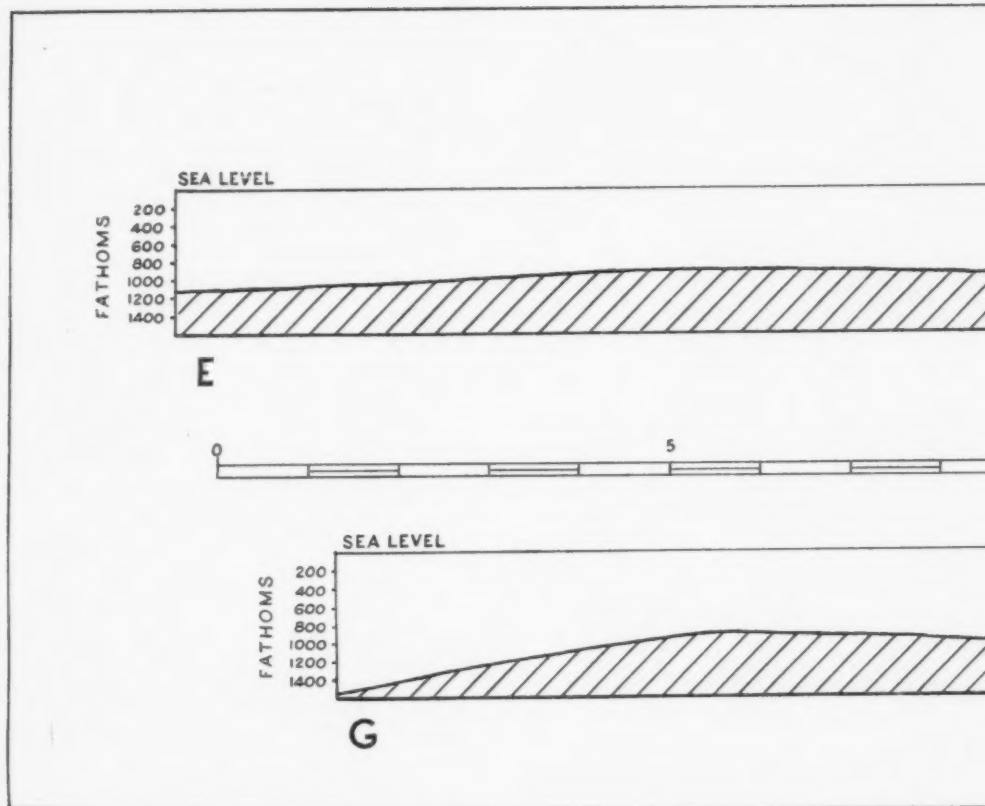
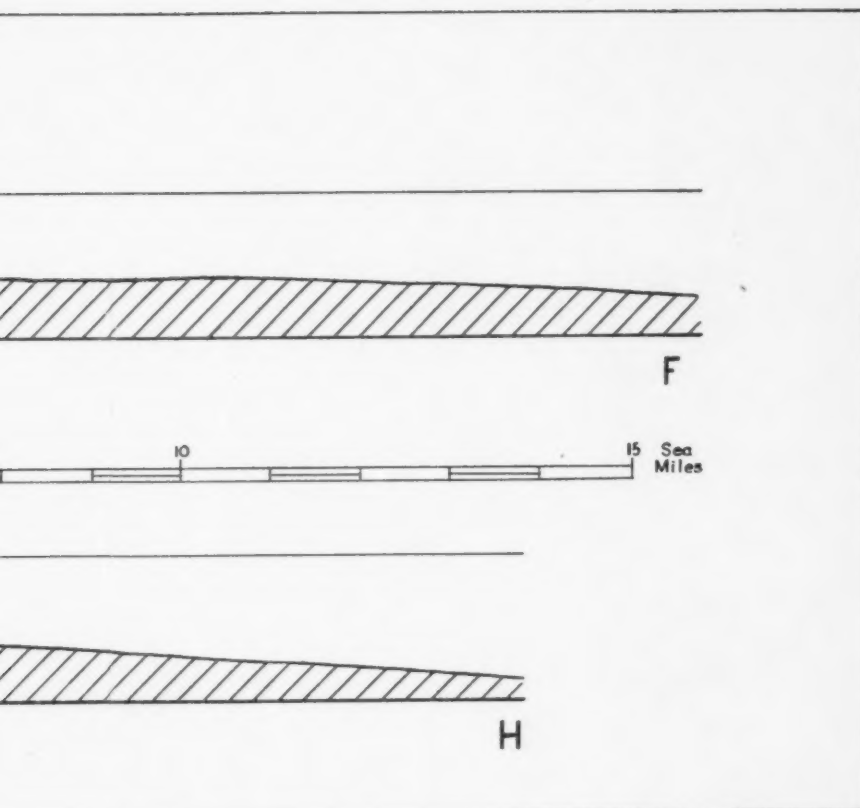
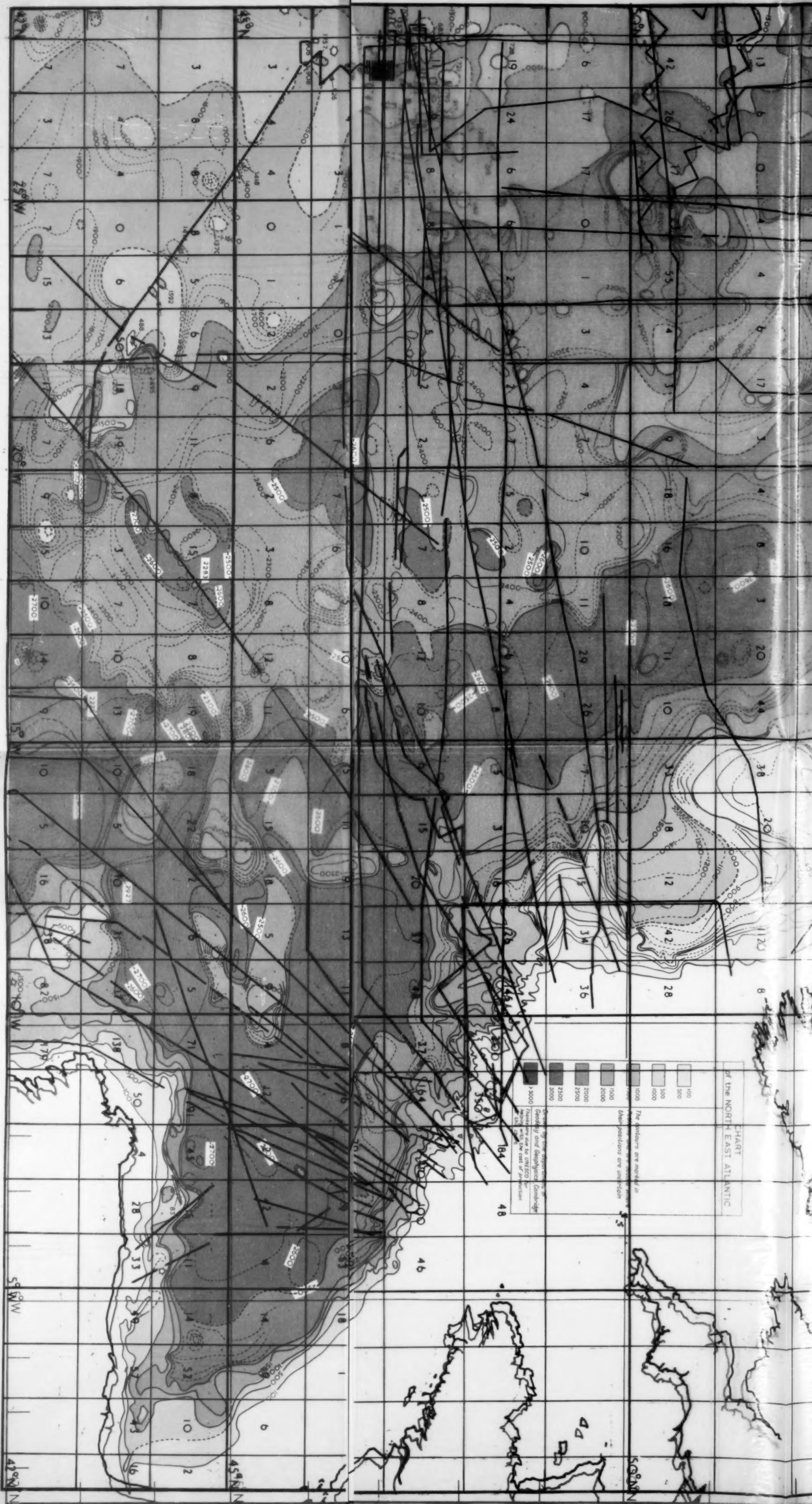


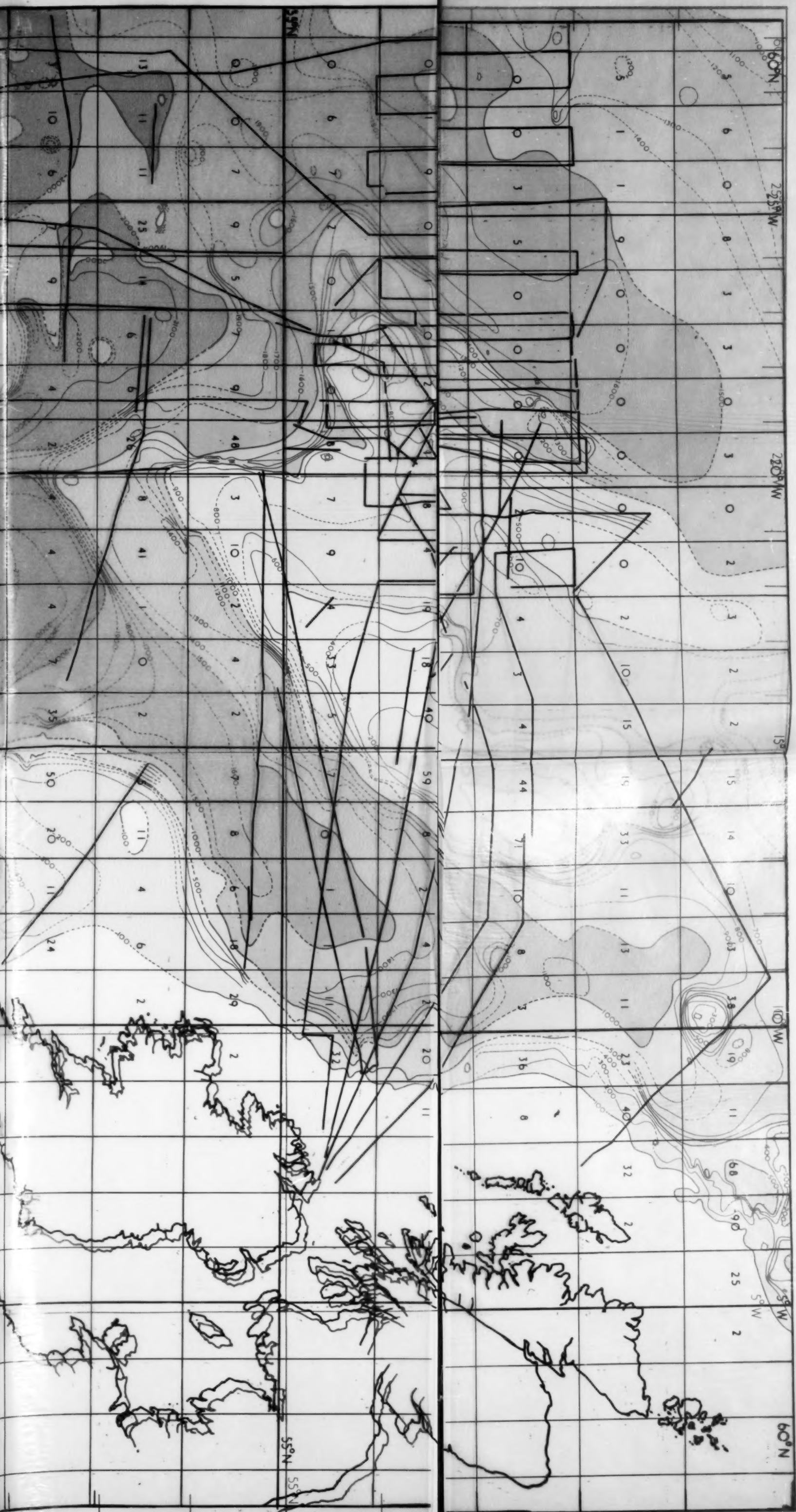
Fig. 6. Natural profiles through David Seaknoll showing

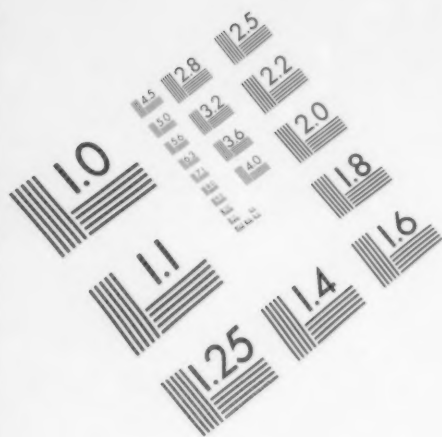


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showing relatively flat top with an easterly tilt.

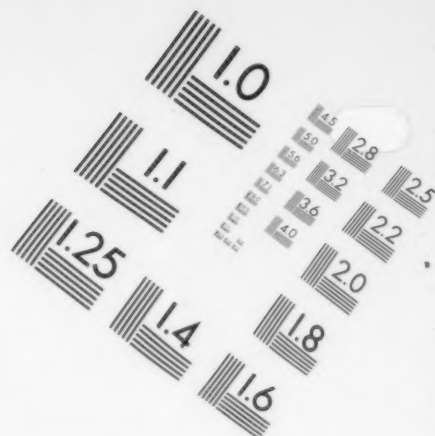




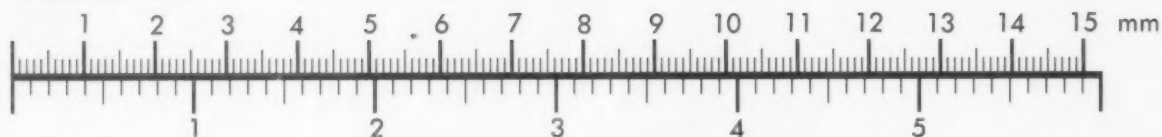


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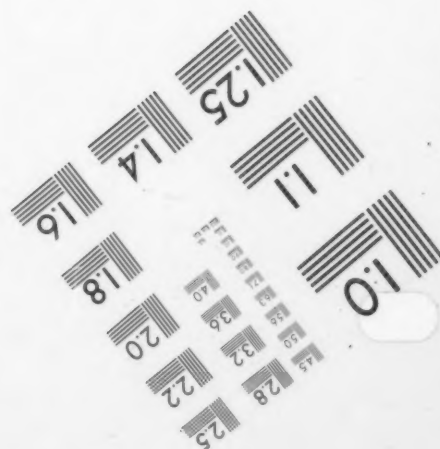
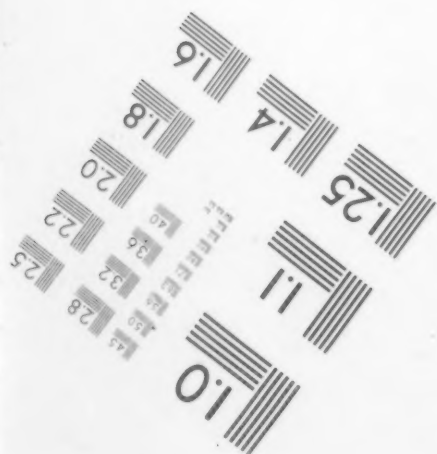
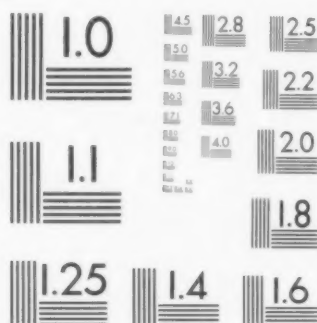
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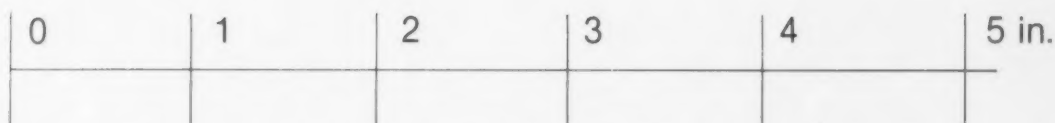
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